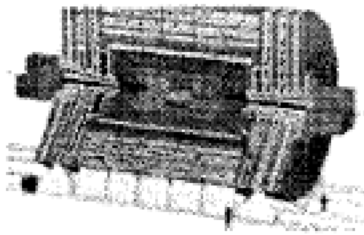


US CMS
the
Compact
Muon
Solenoid

Dan Green
Rice University
Colloquium

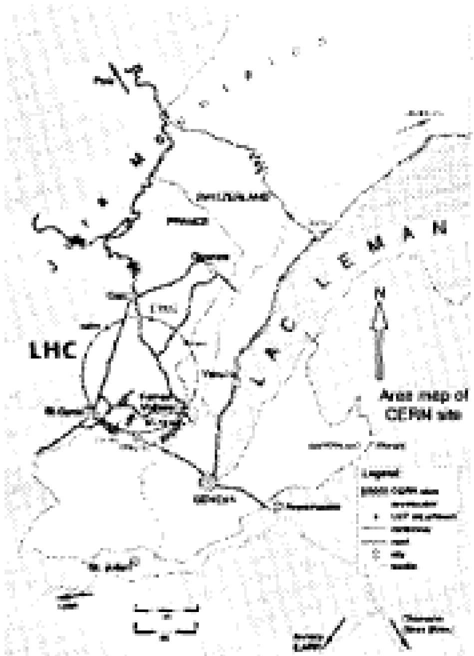
The Physics of the Large Hadron Collider

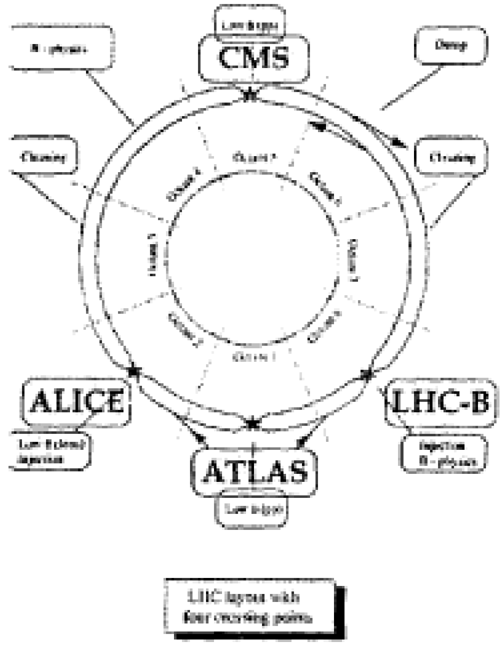
Dan Green
Fermilab

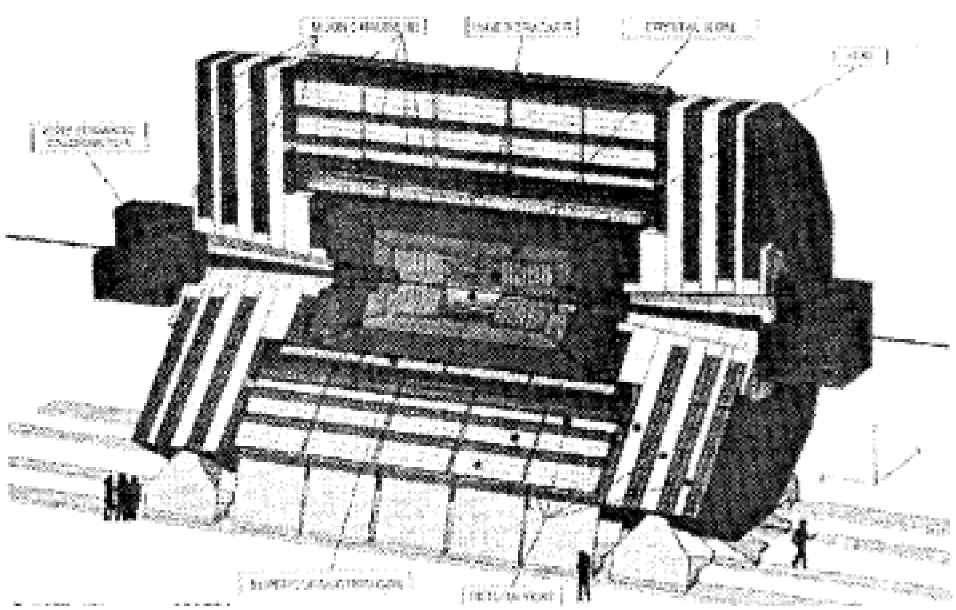
European Center for Nuclear Research - CERN

Large Hadron Collider - LHC

Compact Muon Solenoid - CMS







High Energy Physics - "Natural Units"

The dimensions of a quantity, indicated by [ ], are all taken to be energy in HEP. Momentum and mass are given the dimensions of energy, pc, mc^2. The basic energy unit is the electron Volt, the energy gained when an electron falls through a potential of 1 Volt.

The connection between energy and time, position and momentum is supplied by Planck's constant, $h = h/2\pi = 0.2$ GeV*fm, where 1 fm = 10^{-13} cm. Thus, inverse length and inverse time have the units of energy. The Heisenberg uncertainty relation is $\Delta E*\Delta t = h$, $\Delta x*\Delta p = h$.

Charge and spin are "quantized"; they only take discrete values, e or h/2. Fermions have spin 1/2, 3/2 ..., while bosons have spin 0,1,.... The statistics obeyed by fermions and bosons differs profoundly. Bosons can occupy the same quantum state - e.g. superconductors, laser. Fermions cannot (Pauli Exclusion Principle) - e.g. the shell structure of atoms.

Units

SPIN (the internal angular momentum of the particle): in units of $\hbar$, where $\hbar = h/(2\pi) = 6.58 \times 10^{-25}$ GeV·s = 1.05×10^{-34} J·s.

ELECTRIC CHARGE: in terms of the proton's charge (+1, or in SI units, 1.60×10^{-19} coulomb).

ENERGY: in electron volts (eV), the energy gained by 1 electron in crossing a potential of one volt. 1 eV = 1.60×10^{-19} joule.

MASS: in GeV/c^2, (remember $E = mc^2$). 1 GeV = 10^9 eV. (The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.)

Size and Energy of the Probe

In order to "see" an object of size r one must use "light" with a wavelength λ < r. Thus, visible light with λ ~ 3000 A (1 A = 10^{-8} cm, ~ size of an atom) can resolve bacteria. Visible light comes from atomic transitions with ~ eV energies (h = 2000 eV*A).

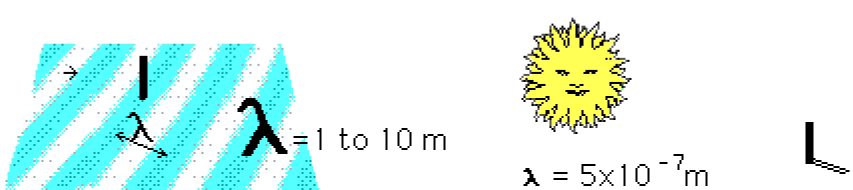
To resolve a virus, the electron microscope with keV energies was developed, leading to an increase of ~ 1000 in resolving power.

To resolve the nucleus, 10^5 time smaller than the atom one needs probes in the GeV (10^9 eV) range. The size of a proton is ~ 1 fm = 10^{-13} cm.

The large Hadron Collider (LHC) at the CERN will explore Nature at the TeV scale or down to distances ~ 0.001 fm.

A Better Microscope...

The best scanning electron microscopes can show only fuzzy pictures of atoms. To see anything smaller you must use smaller wavelengths, λ. For example, the large wavelengths of water waves don't show any effects of a small vertical pole in their paths. But the shorter wavelengths of light give a shadow for that pole.



Energy and wavelengths are inversely related:

$$E \propto 1/\lambda.$$

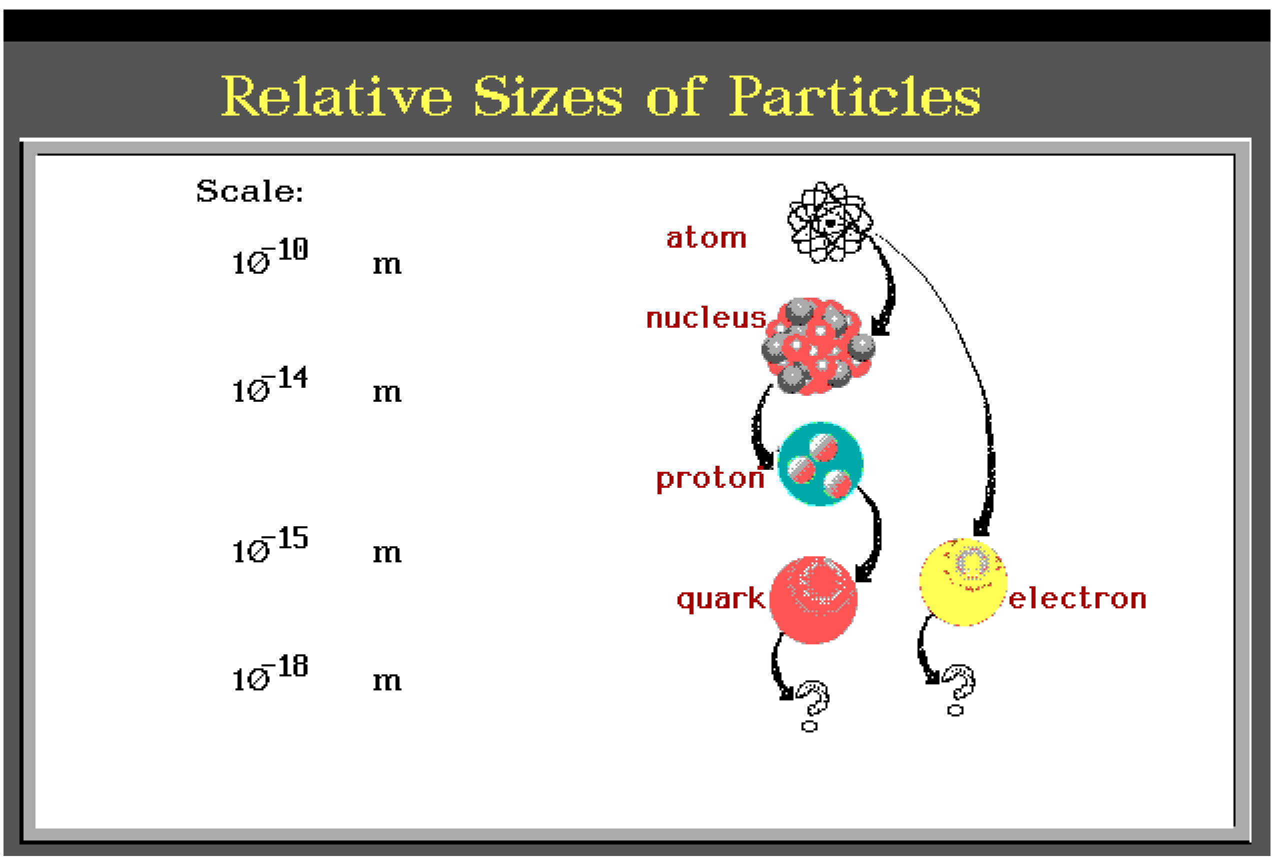
So the smaller the particles that you want to see, the more energy you need from your accelerator.

The Quest for Fundamental Particles

As the tools available to our science have improved, the "cosmic onion" has revealed layer upon layer.

Bulk matter was found to be mostly empty space. The atoms in a solid are packed ~ together, where a typical atom has a characteristic size ~ 1 A = 10^{-8} cm. The mass of an atom is concentrated in the nucleus (A nucleons, Z protons, and A-Z neutrons). The size of a proton is ~ 1 fm = 10^{-13} cm.

In the 1970s the proton was observed to consist of point like quarks. This behavior is resolved at energies ~ 10 GeV or 0.02 fm. Since that time energies up to 100 GeV ~ 0.002 fm have been explored and the quarks and leptons still appear to be point particles. The LHC will extend the search to ~ 1 TeV or 0.0002 fm.



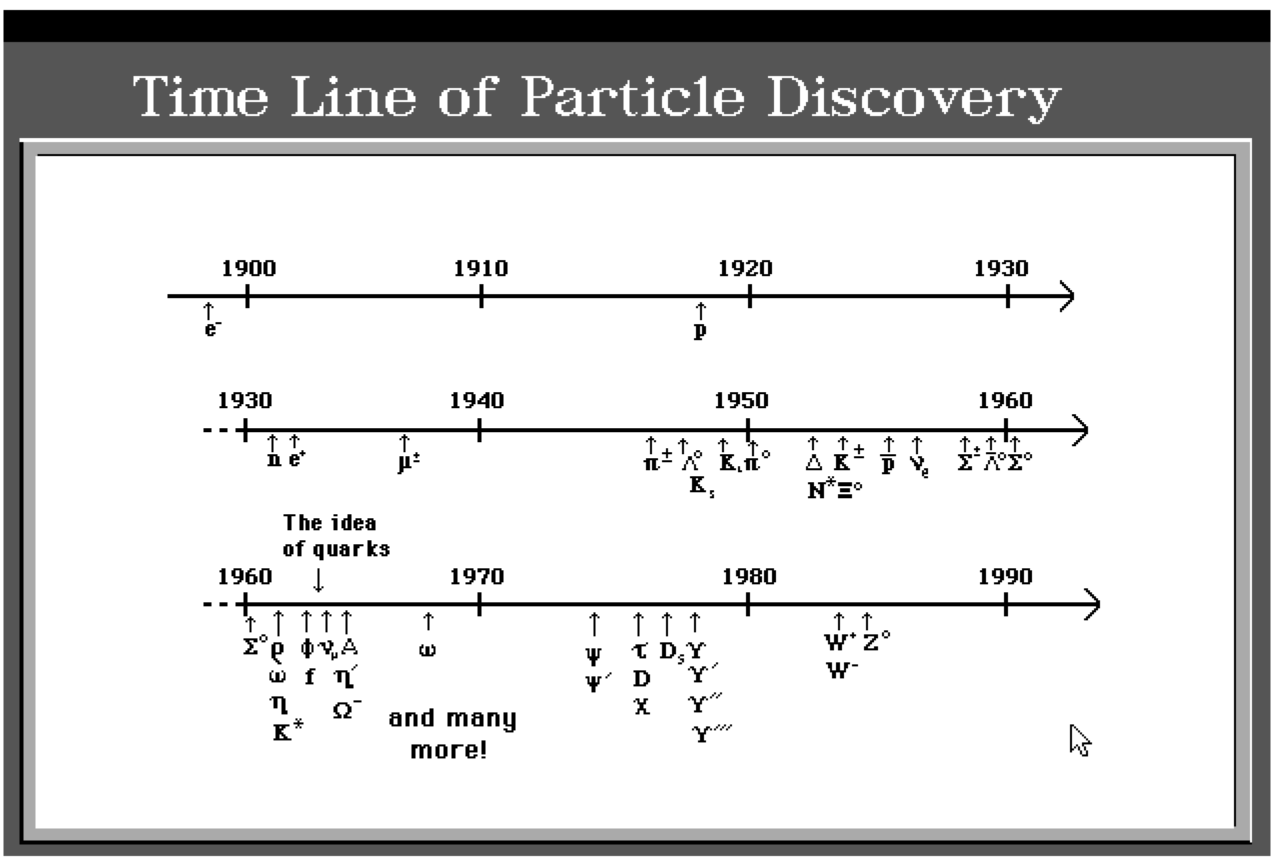
"Particle Physics" in the 20th Century

The e^- was discovered by Thompson ~ 1900. The nucleus was discovered by Rutherford in ~ 1920. The e^+, the first antiparticle, was found in ~ 1930. The μ , indicating a second generation, was discovered in ~ 1936.

There was an explosion of baryons and mesons discovered in the 1950s and 1960s. They were classified in a "periodic table" using the SU(3) symmetry group, whose physical realization was point like, strongly interacting, fractionally charged "quarks". Direct evidence for quarks and gluons came in the early 1970s.

The exposition of the 3 generations of quarks and leptons is only just, 1996, completed. In the mid 1980s the unification of the weak and electromagnetic force was confirmed by the W and Z discoveries.

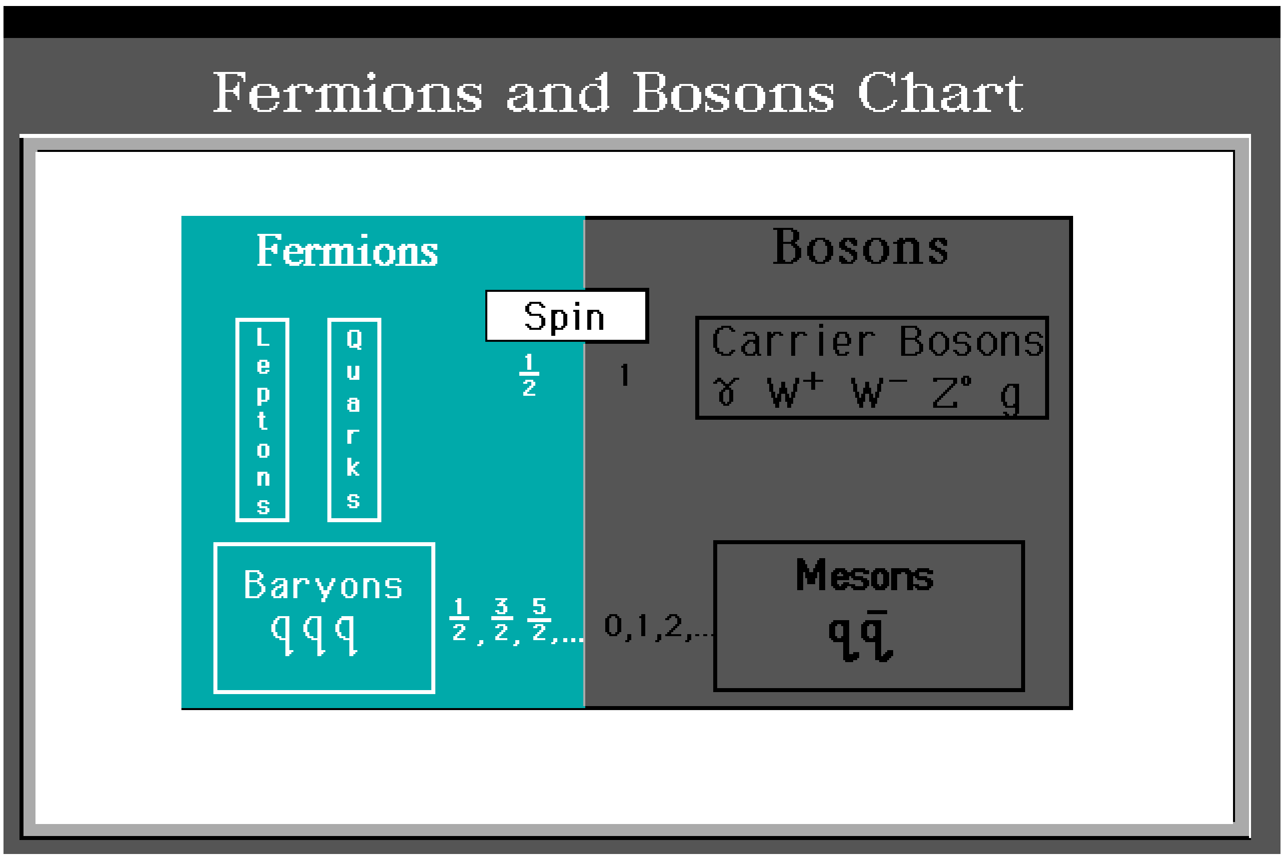
The LHC, starting in 2005, will be THE tool to explore the origin of the breaking of the electroweak symmetry (Higgs field?) and the origin of mass itself.



The Standard Model
of Elementary Particle Physics

Matter consists of half integral spin fermions. The strongly interacting fermions are called quarks. The fermions with electroweak interactions are called leptons. Composite fermions are the qqq baryon states.

The forces are carried by integral spin bosons. The strong force is carried by the gluon (g), the electromagnetic force by the photon (γ), and the weak interaction by the W^+, Z^o, and W^+.



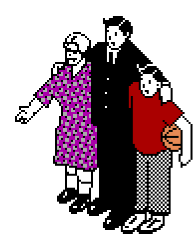
The Generation Mystery

Over the last 50 year the existence of multiple generations has been experimentally established. The ν was hypothesized to account for the β decay spectrum of nuclei. The μ was first seen (1936) in cosmic rays, while the strange quark (s) was seen in cosmic rays and accelerator experiments in the 1950s. The charmed quark (c) was discovered in the mid 1970s, completing the second generation. This was followed immediately by the discovery of the τ lepton, indicating a third generation. The beauty (b) quark was discovered within 2 years and the gluon (g) was inferred from the radiative topology of jet events. The W and Z were discovered in the mid 1980s, while the top quark(t) was only observed in 1996. That there are only 3 generations was inferred from the decay width of the Z and from primordial nucleosynthesis.

WHY?

Generations

All stable matter is made from particles in just the first generation. Physicists had though that they understood all matter until the muon (μ), the first particle of the second generation, was discovered in 1936. It is said that the physicist, I.I. Rabi, asked, "Who ordered THAT?" when he heard of the new particle. Today we still are trying to answer his question!



Related questions are:
How many more generations exist?
Why are the masses the way they are?
Are there other leptons and quarks that are simply too heavy to have been produced in any experiment to date?

1st	2nd	3rd
u	c	t
d	s	b
e	μ	τ
ν_e	ν_μ	ν_τ

The 3 Quark Generations

The quarks are point like fundamental particles possessing both strong and electroweak interactions. They have fractional charge, q = 2/3 and q = -1/3 in units of e. The top mass is now known to be 176 +- 12 GeV. The pattern of masses in not understood. In the SM the masses are simply input parameters.

The u and d are the lowest mass states and make up matter as it appears in the nucleus, p = uud - n = udd. The free n is unstable, but n bound in nuclei have their mass reduced by the negative binding energy, making the n stable.

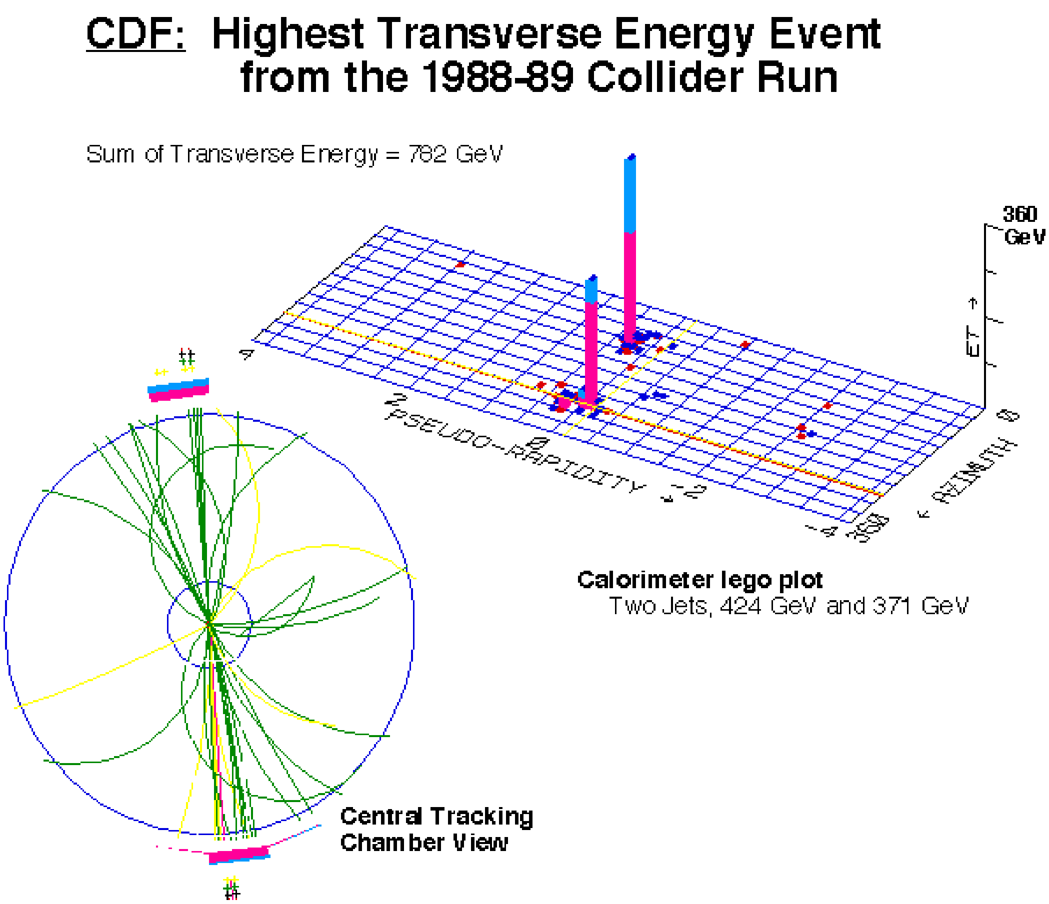
The strong force is mediate by 8 colored gluons. This force is confining in that free quarks and gluons are not possible. The force between p and n is a residual "Van der Waals"type in analogy to the force between neutral molecules as residual to the EM forces binding electrons to nuclei.

Quark Chart

Flavor	Mass(GeV/c^2)	Elect. Charge
u up	4×10^{-3}	$+\frac{2}{3}$
d down	7×10^{-3}	$-\frac{1}{3}$
c charm	1.5	$+\frac{2}{3}$
s strange	0.15	$-\frac{1}{3}$
t top	>89	$+\frac{2}{3}$
b bottom	4.7	$-\frac{1}{3}$

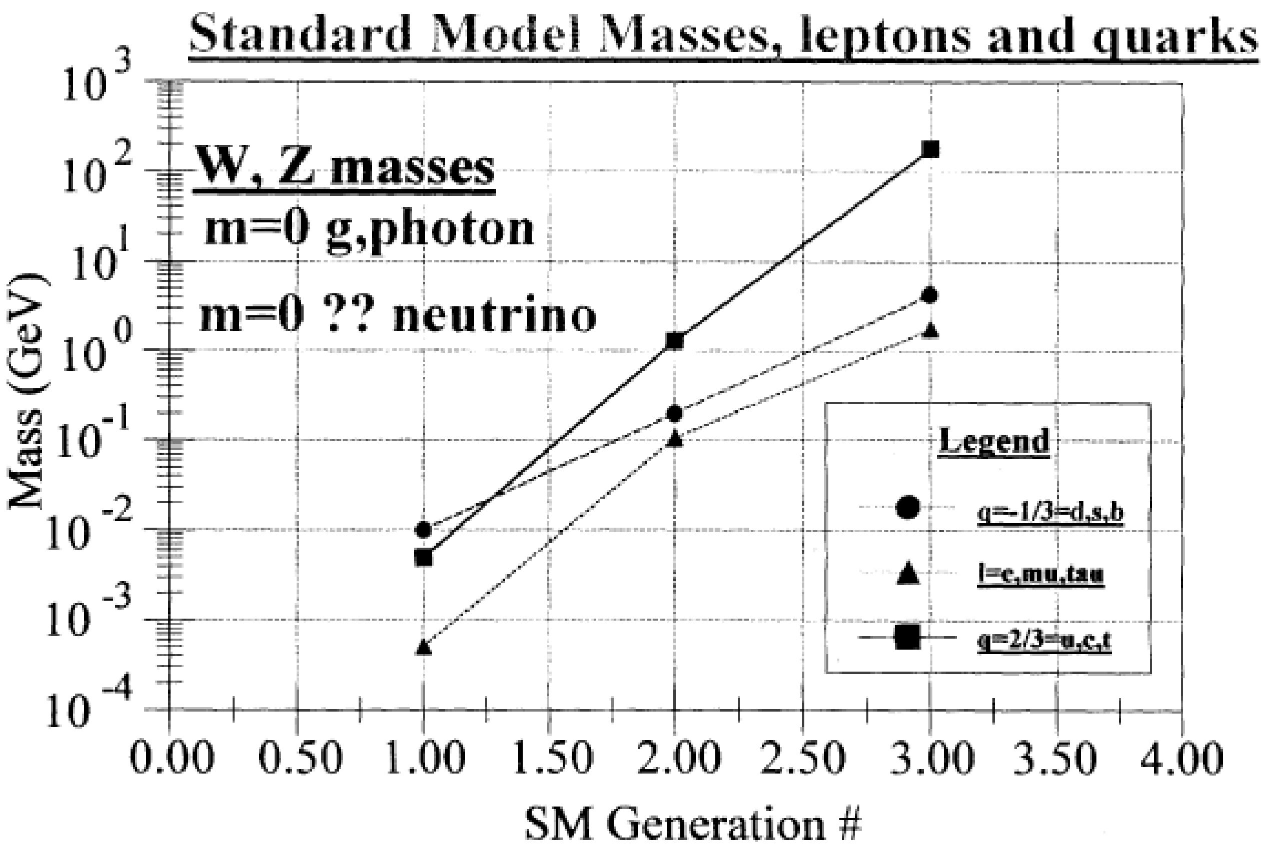
Dijet Events at the Tevatron

The scattering of quarks inside the proton leads to a "jet" of particles traveling in the direction of, and taking the momentum of, the parent quark. Since there is no initial state Pt, the 2 quarks in the final state are "back to back" in azimuth.



The Standard Model
of
High Energy Physics

There are 3 "generations" of quarks and leptons which have identical interactions and different masses. The pattern of those masses is not understood, as we lack the dynamics to predict.



The 3 Lepton Generations

Leptons have electroweak interactions but not strong interactions. They are either charged or neutral. The neutral leptons are called neutrinos. They have only weak interactions, and so are rather difficult to detect. The neutrinos appear to be massless, although there appears to be no reason for this property. For example the photon and gluon are massless because that property is required to preserve gauge invariance. Active research is going on searching for neutrino mass.

The charged leptons are the e, μ and τ. The heavier leptons decay to the e as the lowest mass (stable) state. The pattern of masses of the charged leptons is not understood, nor is the necessity for 3 and only 3 "generations".

Lepton Chart

	Flavor	Mass (GeV/c^2)	Electric Charge
ν_e	e neutrino	$< 2 \times 10^{-8}$	0
e^-	electron	5.1×10^{-4}	-1
ν_μ	μ neutrino	$< 2.5 \times 10^{-4}$	0
μ^-	muon	0.106	-1
ν_τ	τ neutrino	$< 3.5 \times 10^{-2}$	0
τ^-	tau	1.784	-1

The Force Carrier Spin 1 Bosons in the Standard Model

The photon is familiar from 1905 when Einstein identified it as a particle. The W and Z mediate the "weak" force (SU(2) x U(1), 3 +1). In fact, the fundamental strengths of the weak force and the electromagnetic are quite similar. Due to the large mass of the W and Z, the force appears weak for distances > the Compton wavelength of the W. The strong force is mediated by the 8 massless gluons (3 x 3 = 1 + 8 ,SU(3)). The gluons are thought to be permanently confined.

Force Carriers Chart

Electroweak			Strong or Color		
boson	mass (GeV/c^2)	electric charge	boson	mass (GeV/c^2)	electric charge
γ	0	0	gluon	0	0
W^+	80	+1			
W^-	80	-1			
Z^0	91	0			

spin = 1

Electro - Weak Unification

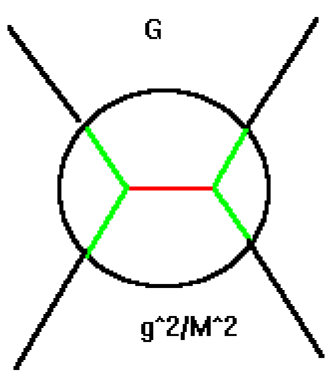
The weak interactions are responsible for nuclear beta decay. The observed rates are slow, indicating weak effective coupling. The decays of the nuclei, n, and m are parametrized as an effective 4 fermion interaction with coupling, $G \sim 10^{-5}$ GeV^{-2}, $\Gamma_\mu \sim G^2 M_\mu{}^5$.

The weak SU(2) gauge bosons, W^+ Z^o W^- , acquire a mass by interacting with the "Higgs boson vacuum expectation value" of the field, while the U(1) photon, γ , remains massless.

$$M_W \sim g_W\langle\phi\rangle$$

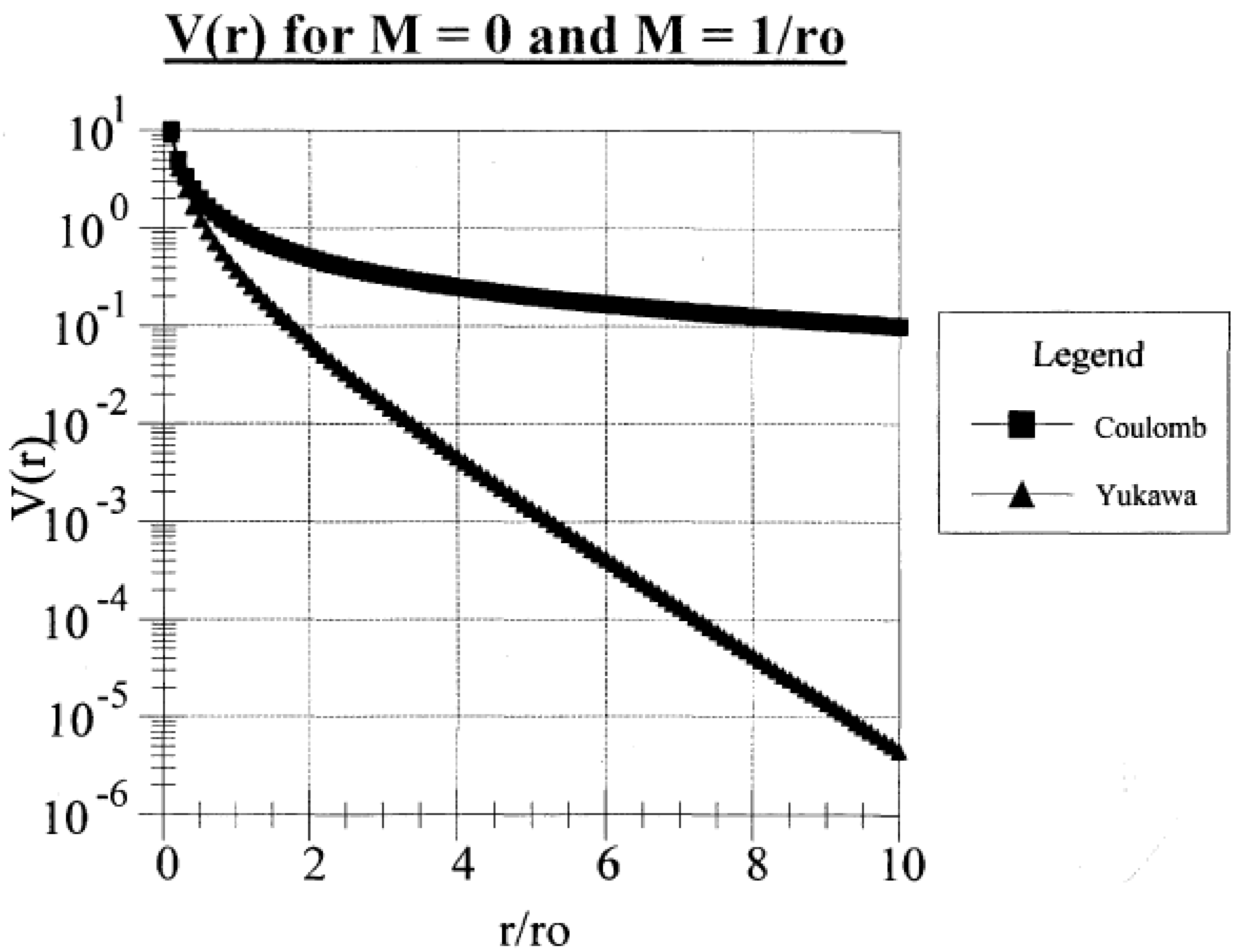
The SU(2) and U(1) couplings are "unified" in that $e = g_W{*}\sin(\theta_W)$. The parameter θ_W can be measured by studying the scattering of $\nu + p$, since this is a purely weak interaction process.

The coupling g_W can be connected to G by noting that the 4 fermion Feynman diagram can be related to the effective 4 fermion interaction by the Feynman "propagator", $G \sim g_W{}^2/M_W{}^2$. Thus, from G and $\sin(\theta_W)$ one can predict M_W. The result, $M_W \sim 80$ GeV was confirmed at CERN in the pp collider. The vacuum Higgs field has $\langle\phi\rangle \sim 250$ GeV.



The Electromagnetic and Weak interactions

The weak interactions are weak only when viewed at low mass scales, or large distances. For M > Mw or r < rw, V(r) is roughly of the same strength, $\alpha \sim \alpha w$, or Vem(r) ~ Vw(r).

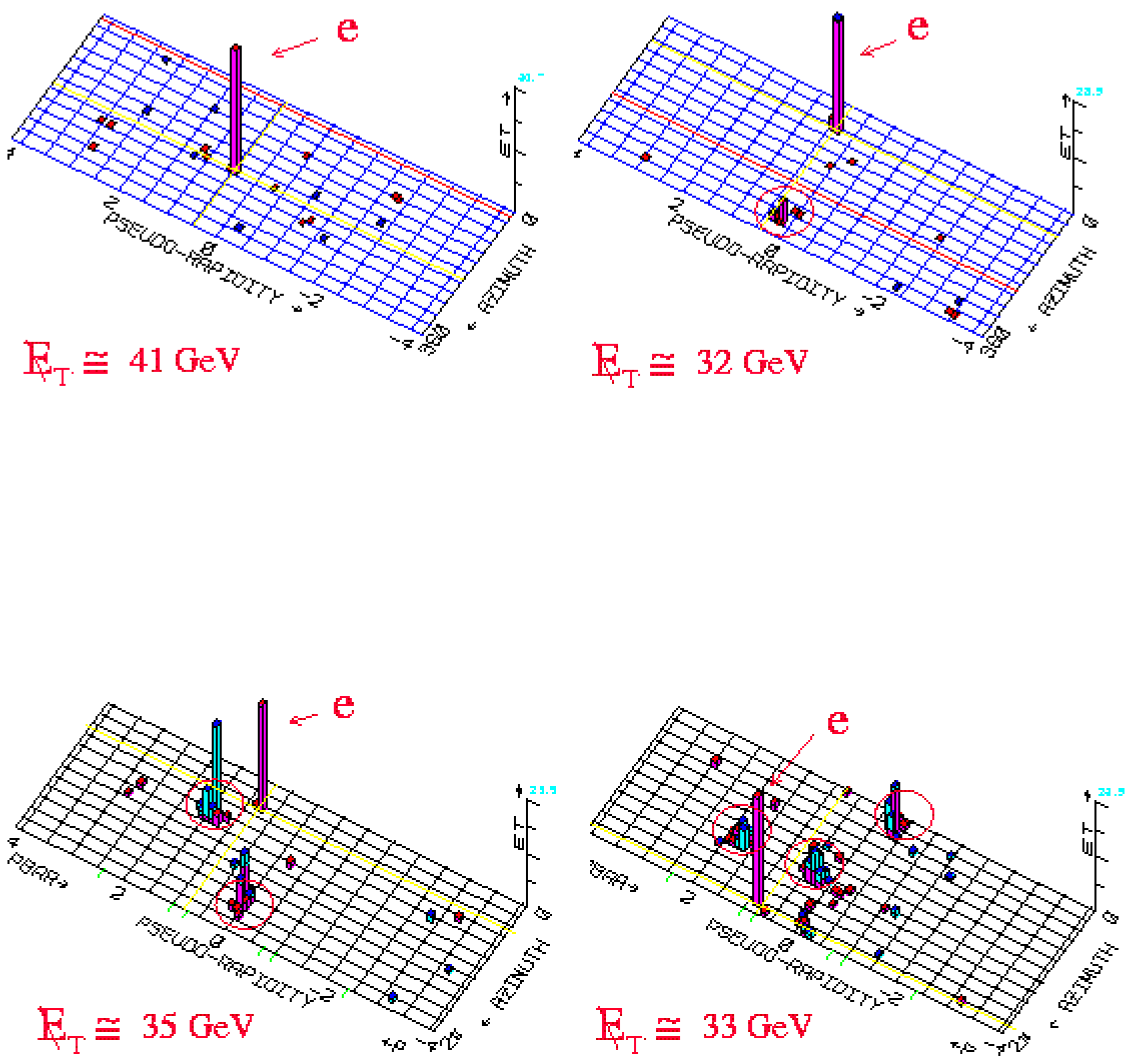


W -> e + ν Events at the Tevatron

The W gauge bosons can decay into quark-antiquarks, e.g. u + d, or into lepton pairs, e + ν_e, μ + ν_μ, τ+ ν_τ. There can also be radiation associated with the W, gluons which evolve into jets.

CDF:

W + 0,1,2,3 jet(s) Events

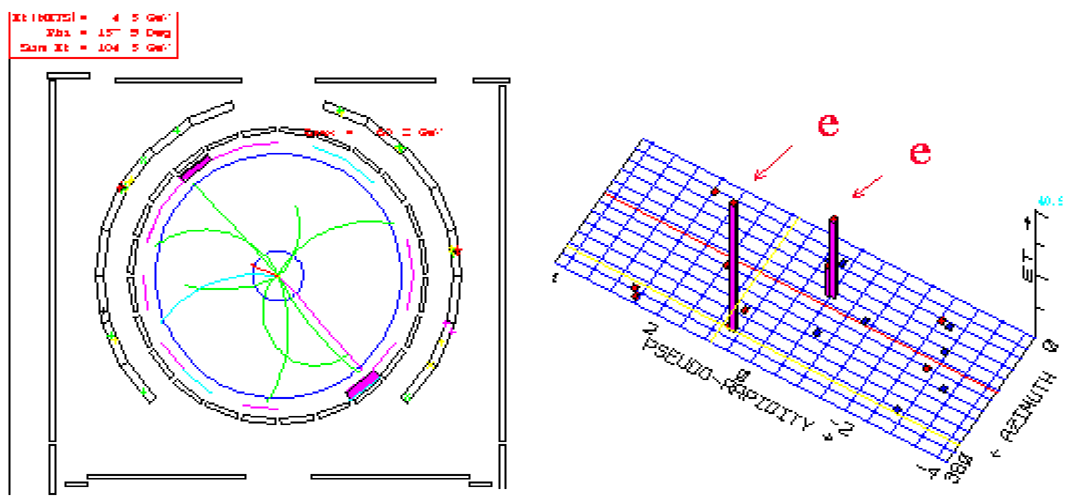


Z --> e + e and μ + μ events at the Tevatron

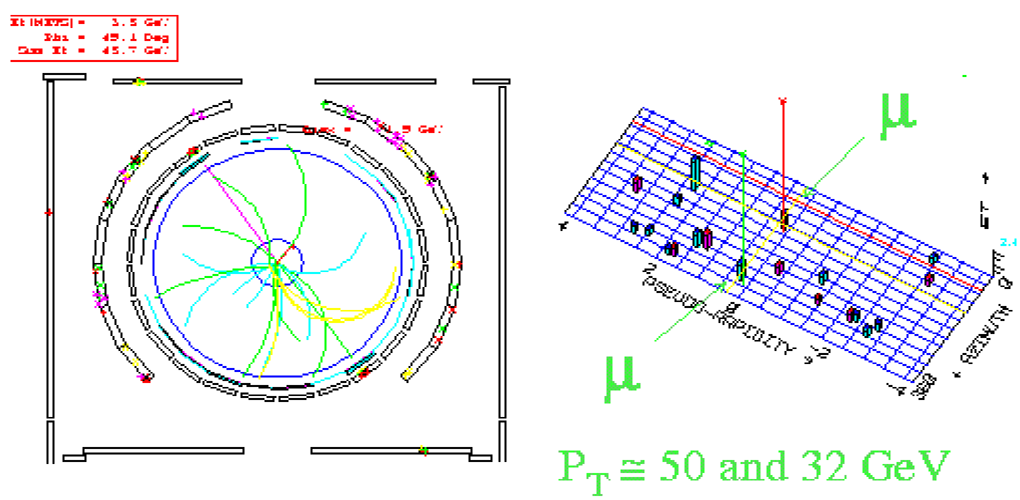
The e appear in the EM and not the HAD compartment of the calorimetry, while the μ penetrate thick material.

CDF:

$Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ Events



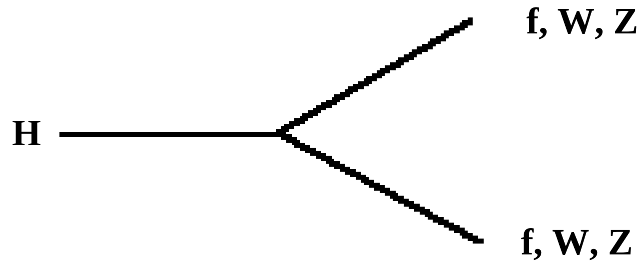
$E_T \cong 44$ and 36 GeV



$P_T \cong 50$ and 32 GeV

Why the Higgs will be discovered at the LHC or before (FNAL, LEP)

The vacuum expectation value of the Higgs field, $<\phi>$, gives mass to the W and Z gauge bosons, $M_W \sim g_W<\phi>$. Thus the Higgs field acts somewhat like the "ether". Similarly the fermions gain a mass by Yukawa interactions with the Higgs field, $m_f = g_f<\phi>$. Although the couplings are just input parameters, the Higgs field gives us a compact mechanism to generate all the masses in the Universe.

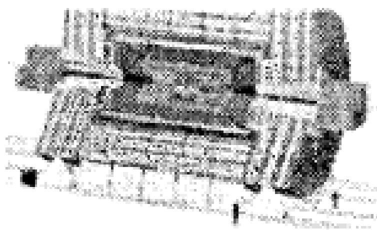


Γ**(H->ff)** $\sim g_f^2 M_H \sim g^2(M_f/M_W)^2 * M_H$, $g = g_W$

Γ**(H->WW)** $\sim g^2 M_H^3/M_W^2 \sim g^2(M_H/M_W)^2 * M_H$

$\Gamma \sim M_H^3$ **or** $\Gamma/M_H \sim M_H^2$ **==>** $\Gamma/M_H \sim 1$ **@** $M_H \sim 1$ **TeV**

$A(e^+e^- \to W^+W^-) \sim \alpha_W/\pi(s/M_W)^2 < 1$ **(partial wave unitarity) ==>** $s \sim M_H < \sim 1$ **TeV. Since the LHC can examine systems with energies up to 1 TeV, a discovery is "guaranteed".**



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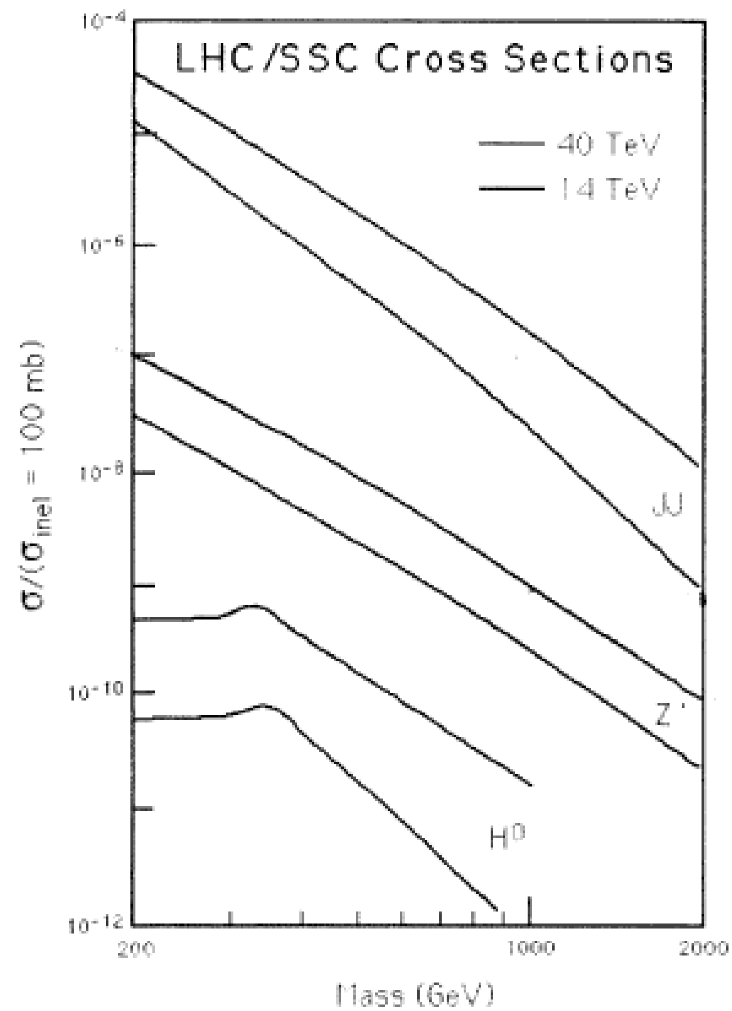
Muon
Solenoid

Dan Green
LHC Experiments
Working Group
EWG
June 10,11 1996

The Physics at the LHC is Compelling



$S/\sqrt{B}$ COMPARABLE $\Rightarrow$
$\mathcal{L}$ MUST BE ~ 10X

21^{ST} CENTURY - TeV MASS

Table 4

New Facilities

Type	Location	CM Energy $\sqrt{s}$ (GeV)	Experiments
Nucleus - Nucleus Collider	BNL, USA RHIC	400	Quark-Gluon Plasma
e^+e^- Collider	CERN, Switzerland LEP II	200	WW γ Coupling
	SLAC, USA SLAC B Factory	10	CP Violation b Spectroscopy
	KEK, Japan	10	
Fixed Target	Fermilab, USA Main Injector	39 (17)	K Beams γ Beams, ν Beams
$\bar{p}p$ Collider		2000	t Decays b Spectroscopy, CP Violation
pp Collider	CERN, Switzerland Large Hadron Collider (LHC)	14000	Higgs Search t Factory b Spectroscopy, CP Violation

WE NEED TO ADDRESS THE
TeV MASS
SCALE

TO MAKE DECISIVE PROGRESS

- EW INTERACTIONS BECOME STRONG

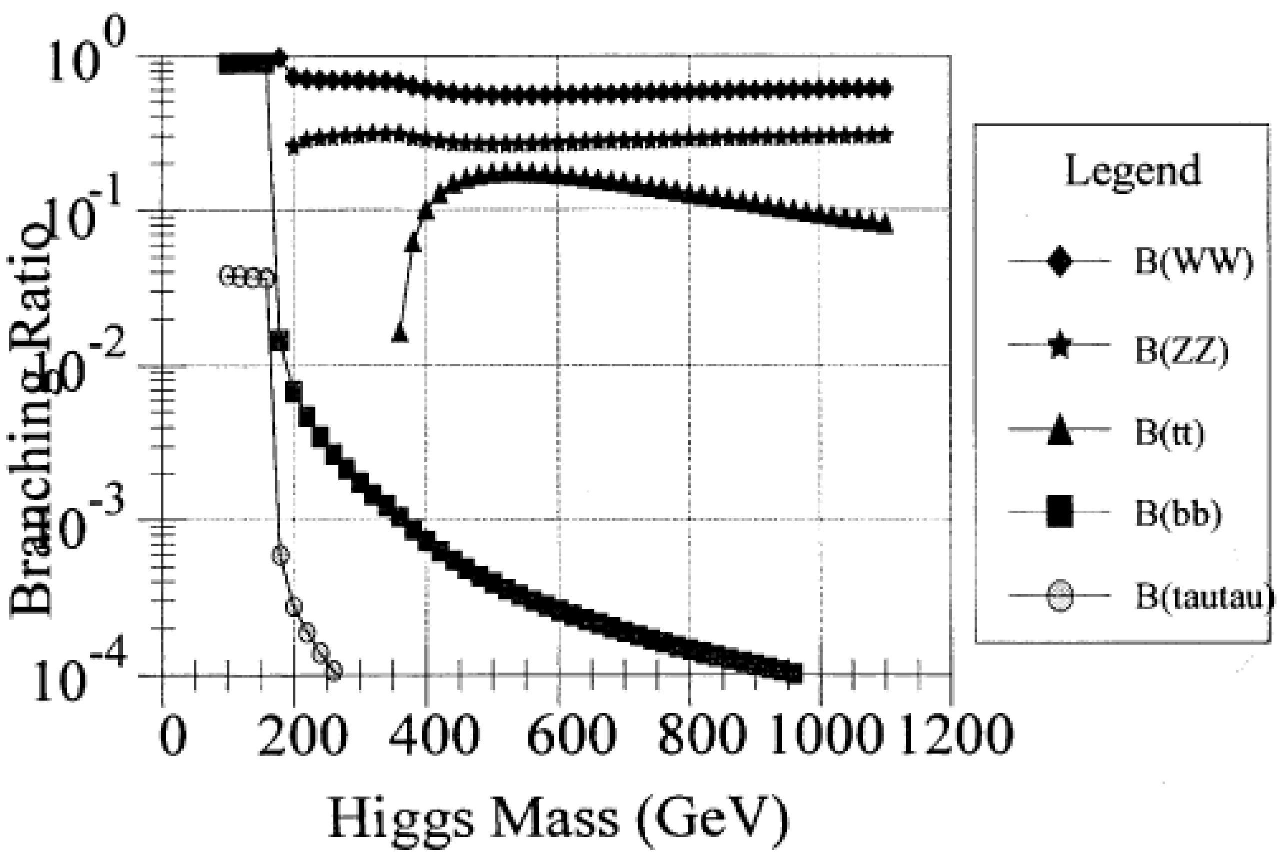
The Higgs Particle in the SM

The vacuum expectation value of the Higgs field is responsible, in the minimal SM, for the breaking of electroweak gauge symmetry, giving mass to the W and Z gauge bosons.

In addition, a Yukawa like interaction, $H \sim g_{ffH} \Psi_f <\phi> \Psi_f$, gives mass to the fermions in the SM. This, in turn, means that the coupling of the Higgs field to the fermions is proportional to the fermion mass.

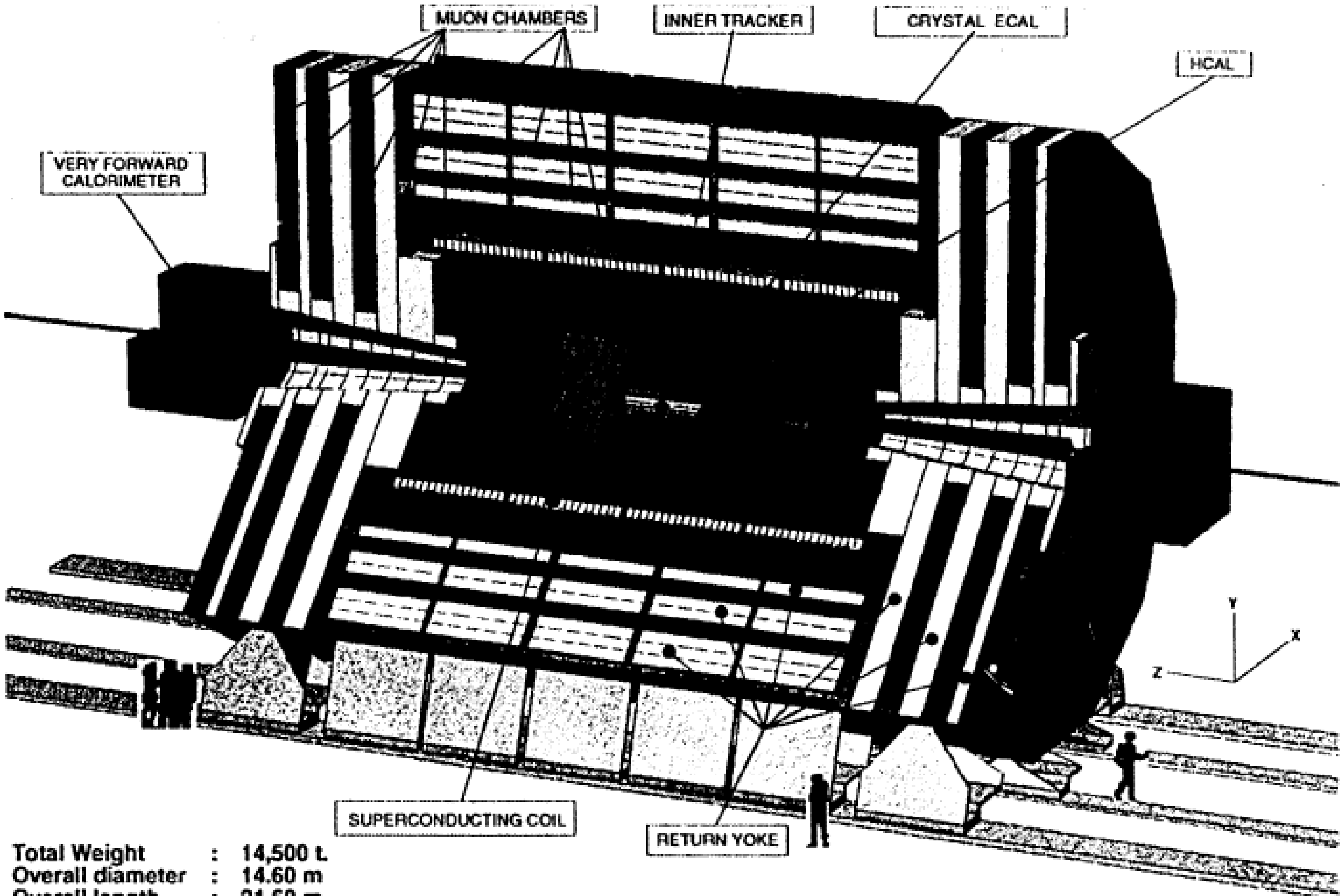
The Higgs mass is unknown. For low masses bb and $\tau\tau$ modes are largest. When energetically allowed WW and ZZ modes dominate. The large top mass makes the tt mode substantial, > 10%.

Higgs Branching Ratios



THE CMS DETECTOR

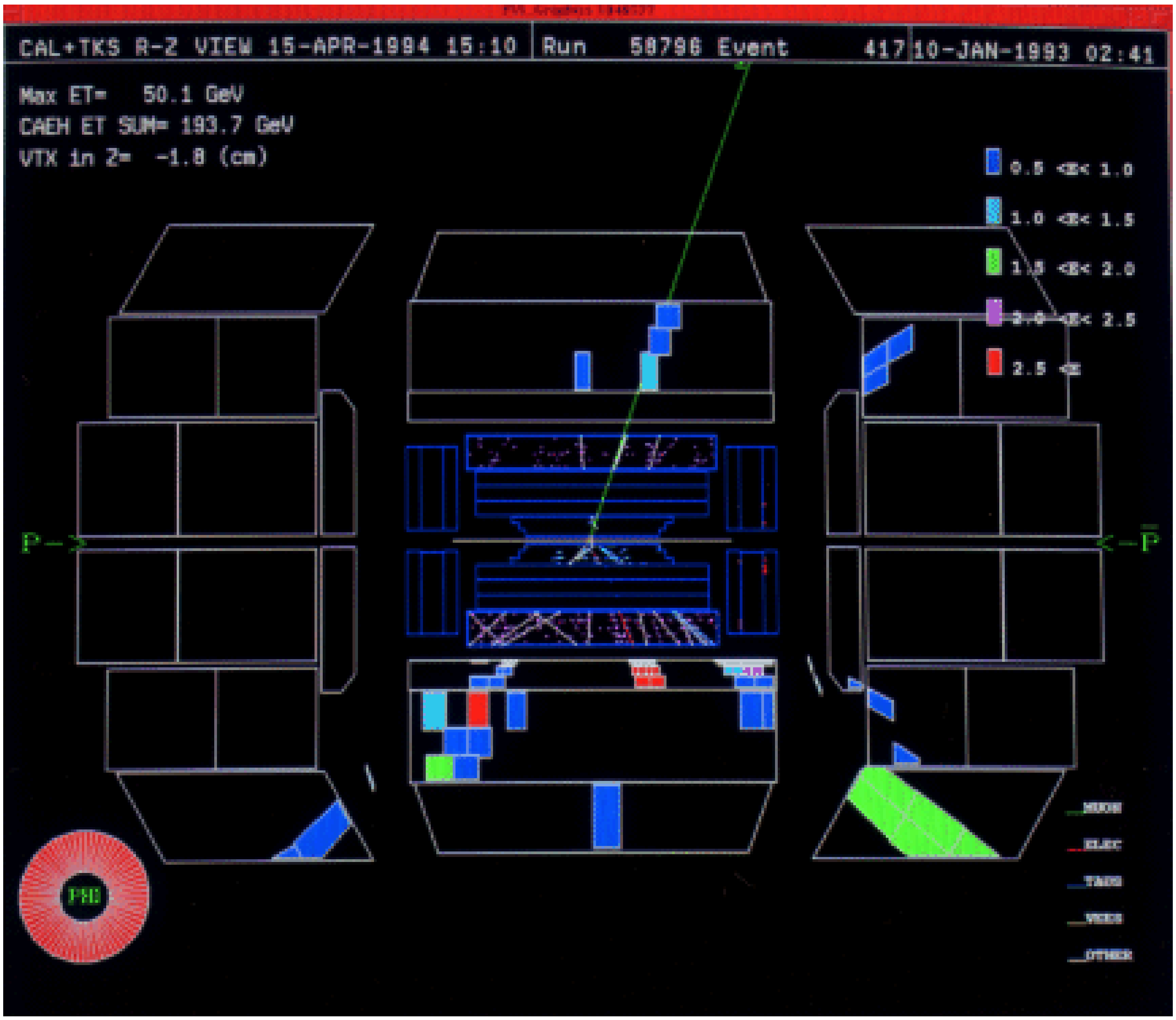
ONE OF THE MOST COMPLEX SCIENTIFIC INSTRUMENTS EVER BUILT



Total Weight	**:**	**14,500 t.**
Overall diameter	**:**	**14.60 m**
Overall length	**:**	**21.60 m**
Magnetic field	**:**	**4 Tesla**

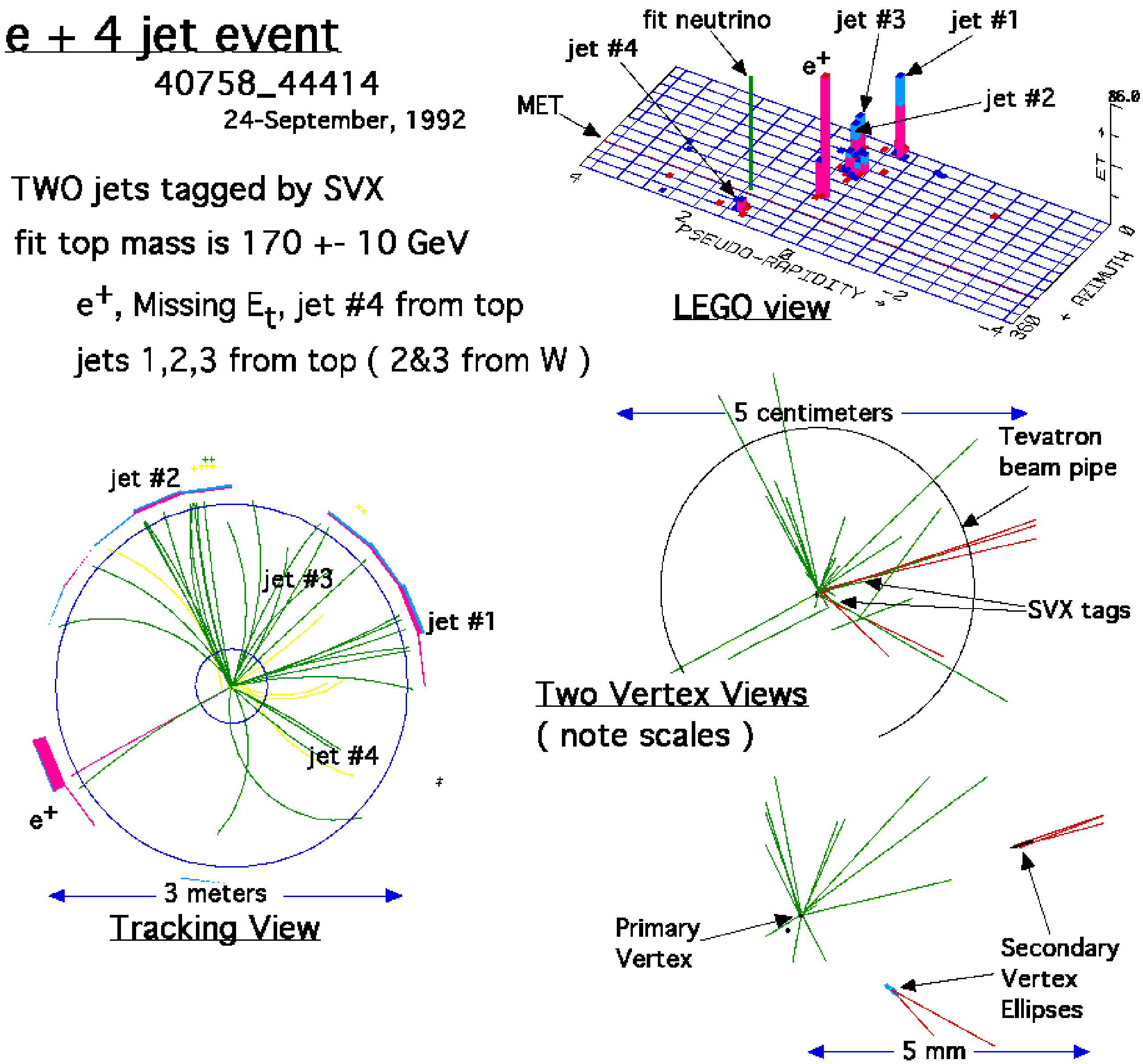
A FNAL Collider (D0) Event

The D0 detector has 3 main detector systems; ionization tracking, liquid argon calorimetry (EM , e , and HAD , jets ,), and magnetized steel + ionization tracker muon , μ , detection/identification. This event has jets, a muon, an electron, and missing energy , ν.



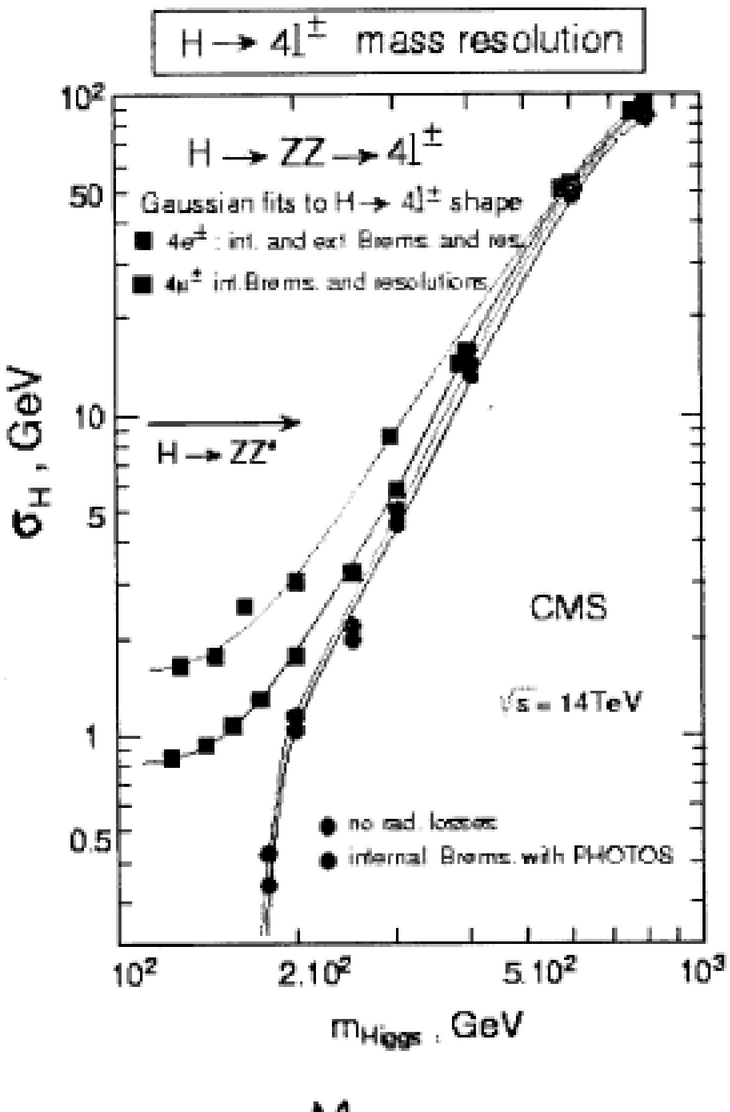
A FNAL Collider (CDF) Event

The CDF detector has 3 main detector systems; tracking - Si + ionization in a magnetic field, scintillator sampling calorimetry, (EM - e, γ and HAD - h), and ionization tracking for muon measurements. Missing energy indicates n in the final state. Si vertex detectors allow one to identify b and c quarks in the event.



The Higgs natural width Γ is proportional to M^3. For masses > 1 TeV, the width is ~ the mass. For very low masses the experimental resolution is $\gtrsim$ the natural width.

Γ_H



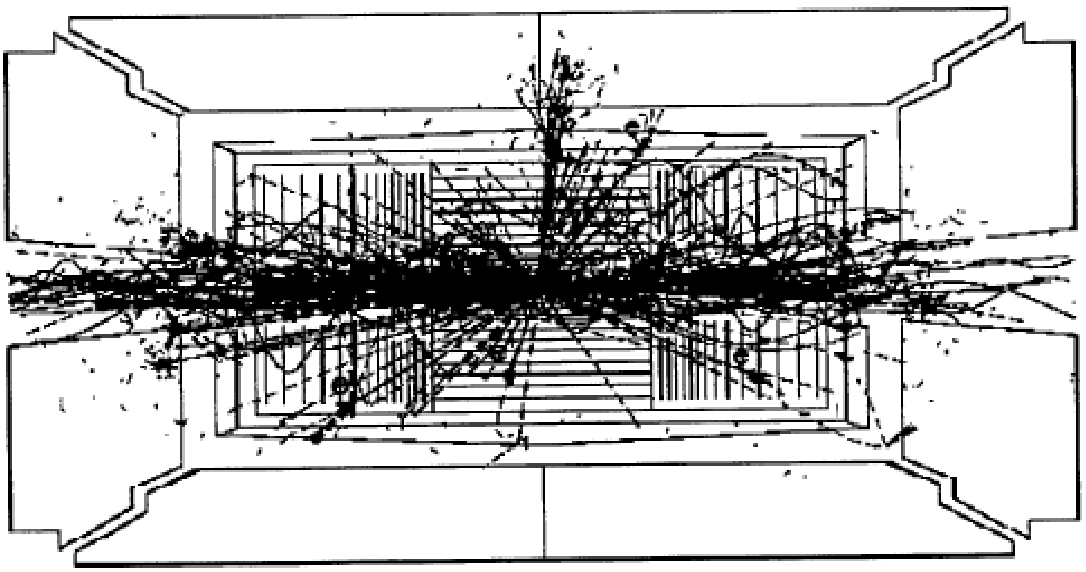
M_H

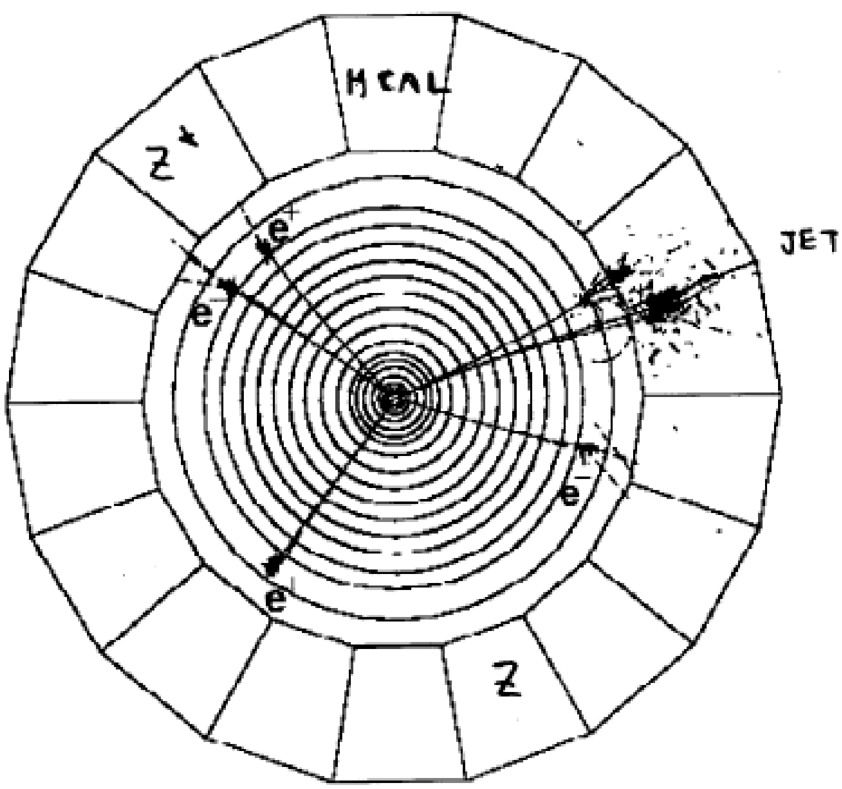
H -> ZZ* -> 4 electrons

FOR $M_H \gtrsim 160$ GeV
$H \to ZZ^*$
OR
$H \to ZZ$ IS
BEST FINAL STATE

CMS full GEANT simulation of

H(150 GeV) --> ZZ*--> 4e





Hadron Calorimeter HCAL

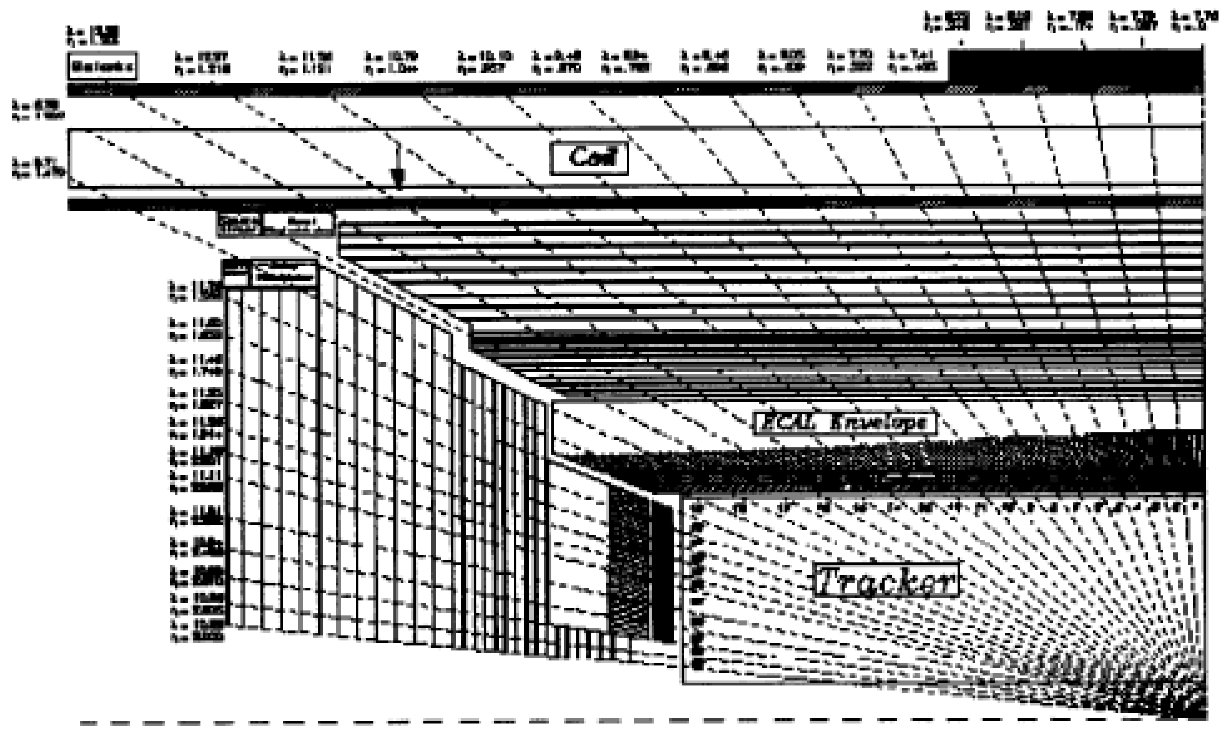
Aim:

- Energy and direction measurement of particle jets, e. g. from W, Z, q → jets and/or missing energy $\not{E}_T$.
- Discover new physics, e. g. heavy Higgs, SUSY particles or composites via $\not{E}_T$ or E_{Tj}.
- Energy resolution:

$$\sigma_E/E - 65\%/\sqrt{E}\ \Phi\ 5\% \quad [E \text{ in GeV}]$$

Requirements:

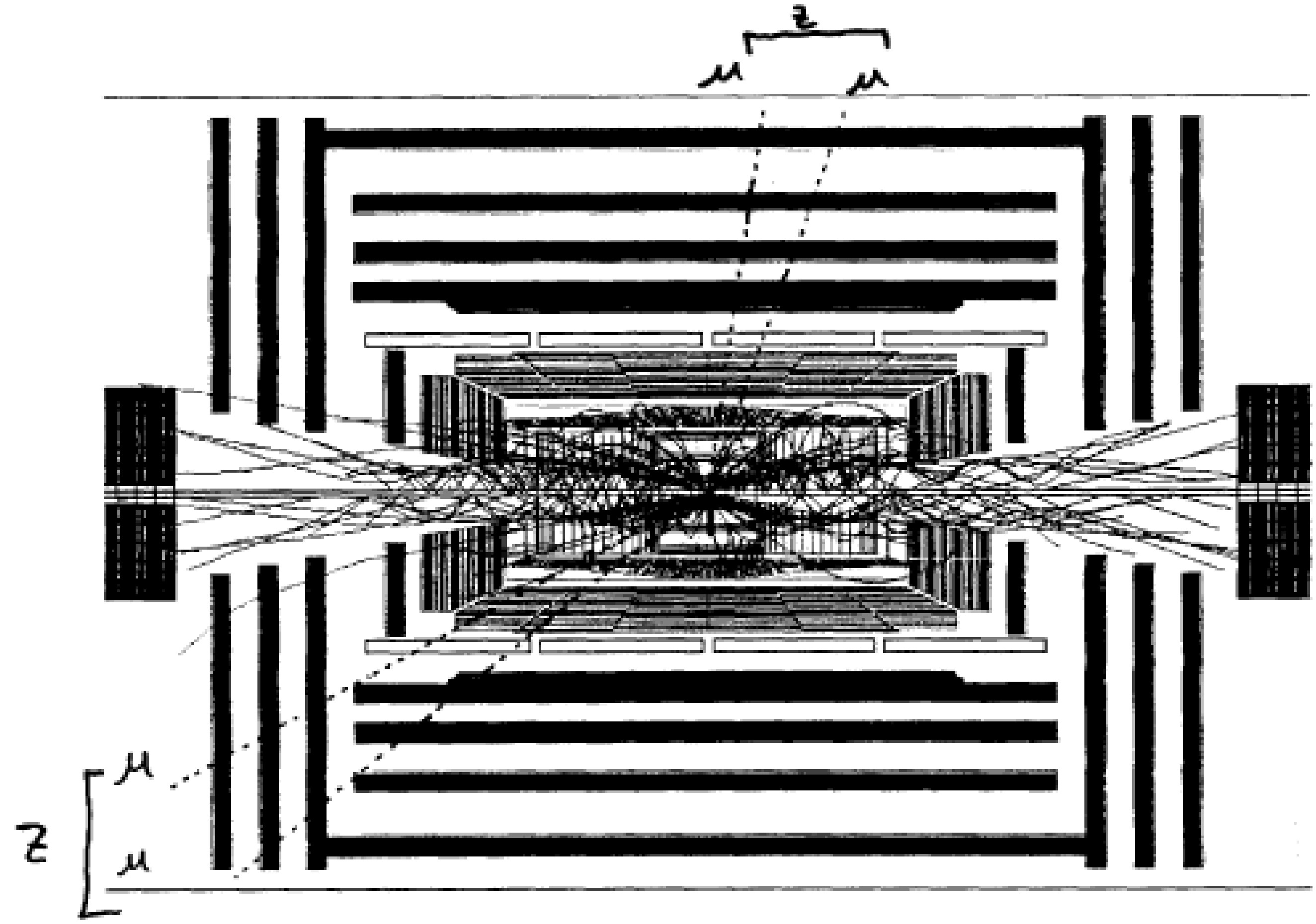
- Extend acceptance to the highest possible η value.
- Get best hermeticity (more important than resolution!) of the HCAL (HB, HF, HV) .
- **Assure adequate sampling depth to avoid leakage.**



The Higgs boson is weakly coupled to ordinary matter. Thus the Higgs mass may be light with respect to the beam energy of 7 TeV. Hence, the Higgs decay products appear at rapidities < 3. In addition, the WW fusion process means that there are forward ($3<|y|<5$) jets with $P_T \sim M_W/2$.

CMS

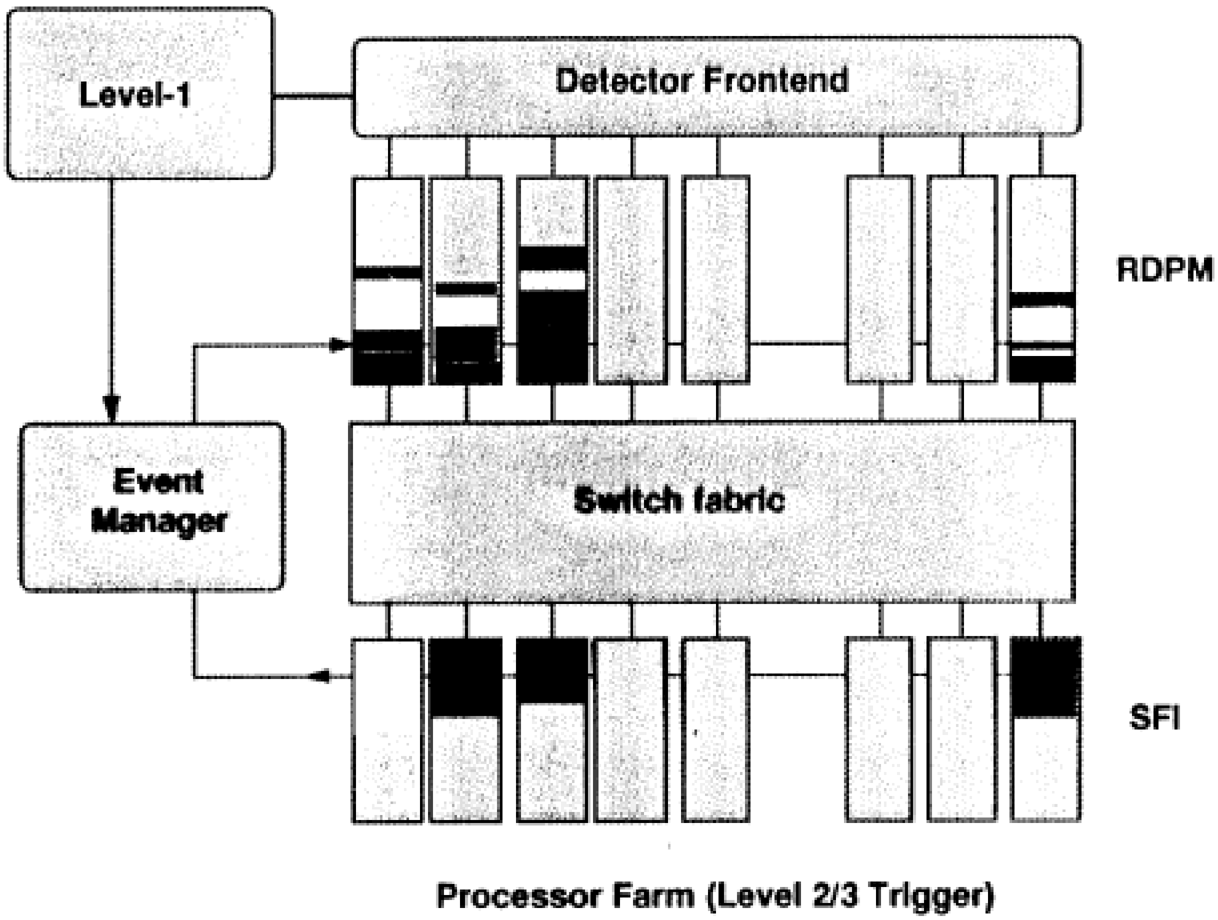
Compact Muon Solenoid



H. Neumeister & N. Sinanis

June 1994

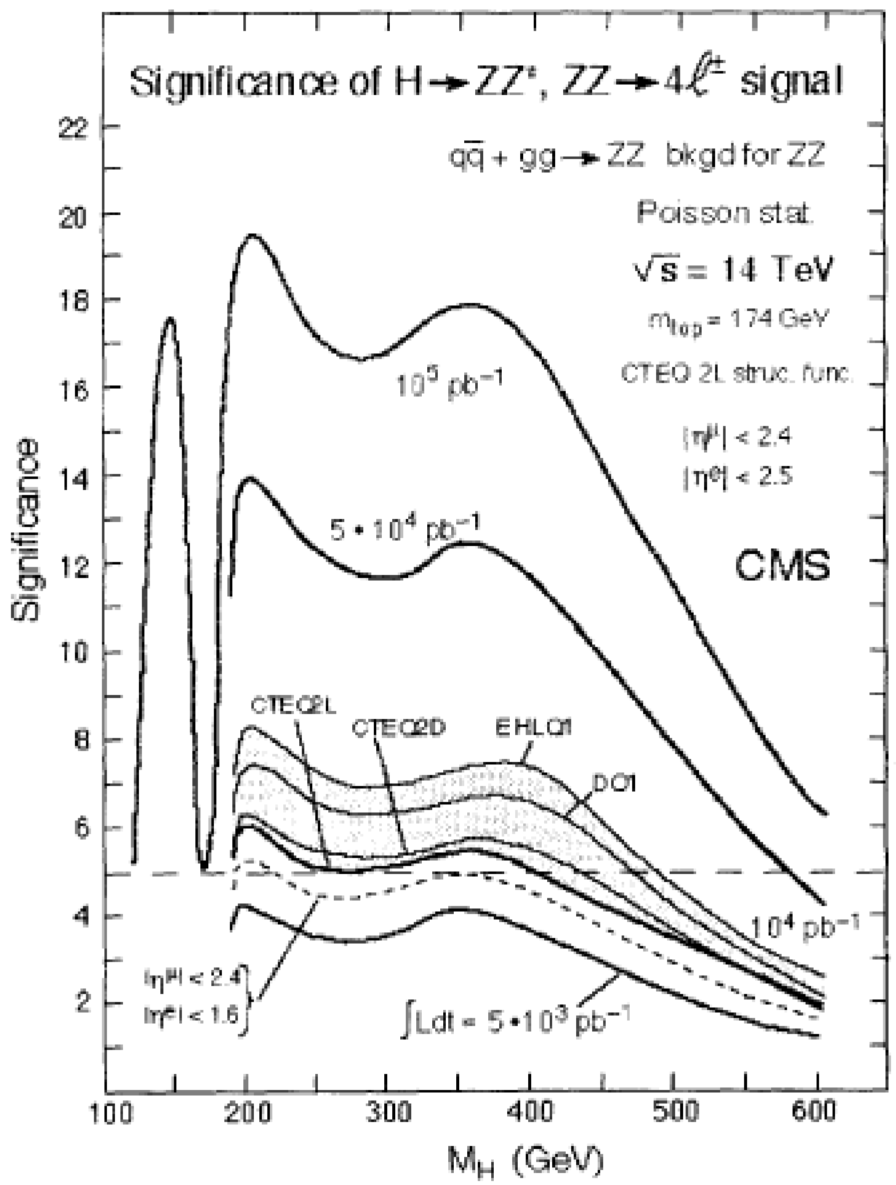
CMS Trigger & DAQ System



- Level 1 Trigger: 40 MHz → 100 kHz
- After Level-1: event in 1000 RDPMs
- Event Building 1: 200 RDPMs → 1 SFI
- Level-2 Trigger: 100 kHz → 1-10 kHz
- Event Building 2: 800 RDPMs → 1 SFI
- Level-3 Trigger: 1-10 kHz → 10-100 Hz

For Higgs masses < 600 GeV the ZZ and ZZ* decay modes into 4l are sufficient.

$$H \rightarrow ZZ^*,\ ZZ \rightarrow 4\ell^{\pm}$$



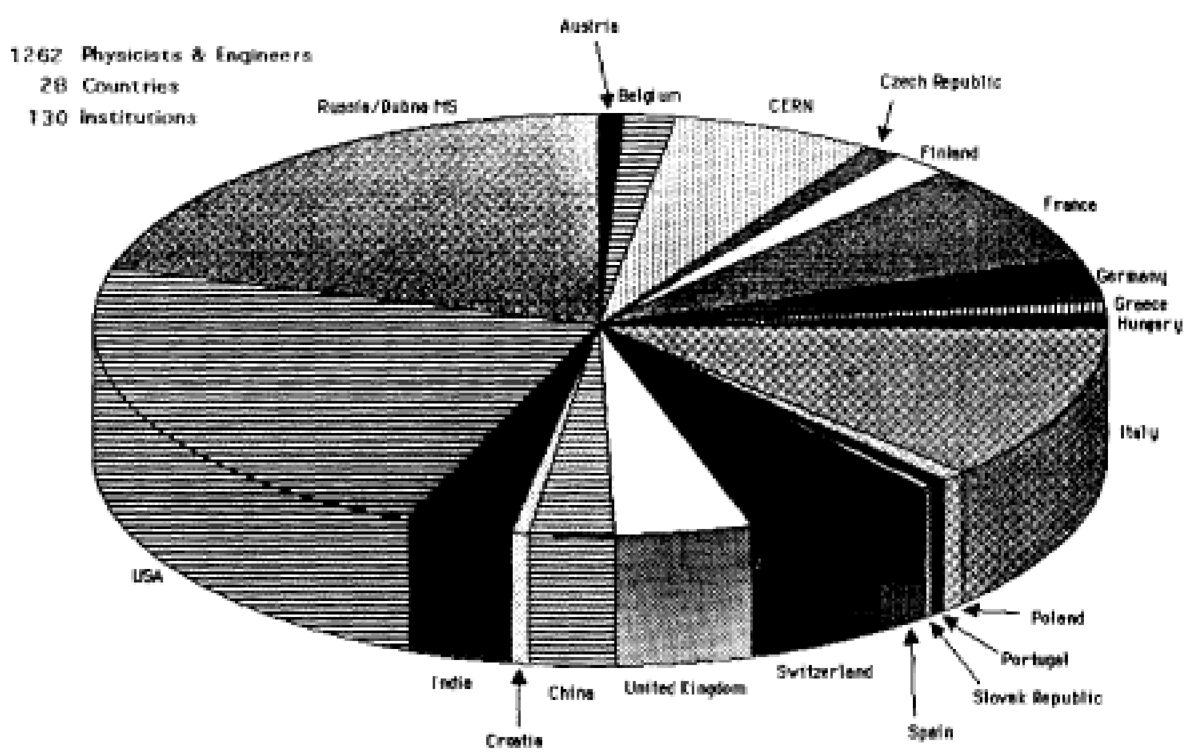
The CMS and US CMS Collaborations

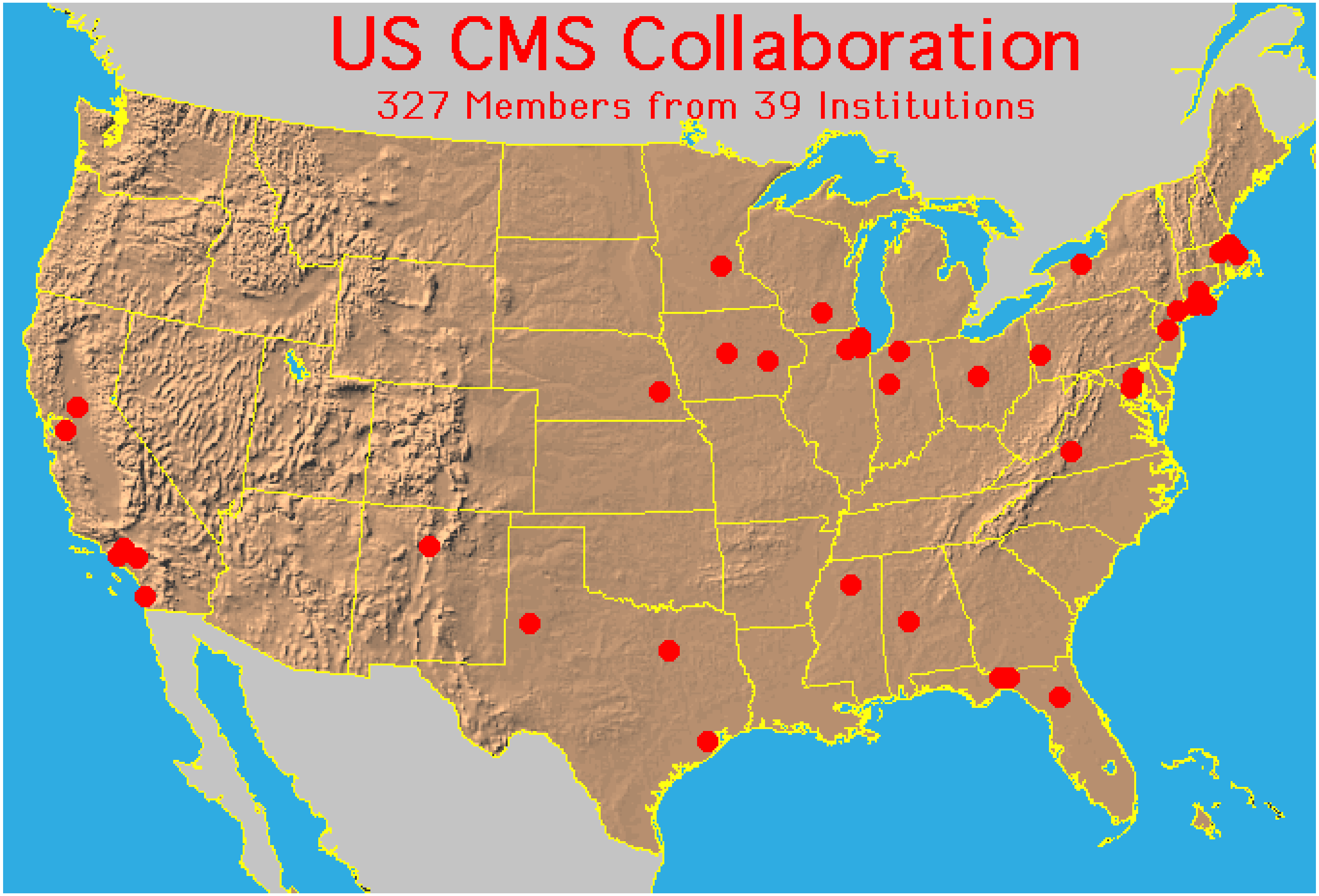
- **The US groups comprise about 20% of the total physicists and engineers in CMS.**

- **The US CMS Collaboration is, therefore, the largest country-wide collaboration within CMS.**

- **The US CMS group is the single largest financial contributor to CMS.**

CMS Collaboration





April 11, 1996

The Interactions Between Particles

The interactions of matter appear to follow from a "gauge principle", that the Physics not depend on a local phase assignment of the quantum wave function. Gravity was the first gauge theory, that Physics be the same for any local label of coordinates. Just as that requirement required the metric, or curvature, or the gravity field, the gauge principle requires the existence of photons, γ , gluons, g , and electroweak bosons, W^+ Z W^-.

Gravity was the first "non Abelian" gauge theory. All mass/energy gravitates, including the field energy (non linearity). Similarly, gluons possess "color" charge, W/Z have weak charge ("flavor"). Photons are not electrically charged, so that EM is a linear theory.

A quantum theory of gravity for point like particle cannot be written without infinities appearing.

Properties of Interactions

Interaction	Gravitational	Weak	Electromagnetic	Strong	
		Electroweak		Fundamental	Residual
Acts on:	Mass-Energy	Flavor charge	Electric charge	Color charge	See info.
Particles Experiencing it:	All	Leptons Quarks	Electrically-charged	Quarks Gluons	Hadrons
Particles Carrying it:	Graviton (not yet observed)	$W^+ W^- Z^0$	γ	Gluons	Mesons
Strength for: 2 quarks at 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
2 quarks at 3×10^{-17} m (relative to e/m)	10^{-41}	10^{-4}	1	60	
2 protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Hints of a SM Extension

- The coupling constants are = at M ~ 10^{16} GeV:
  α/α_W is related by a GUT gauge group.
  Charge quantization is explained.
  Quarks and leptons are related, but only at GUT mass.

- Gravity probably needs to be understood. Gravity is the primordial gauge theory. To succeed, the basic entities must be extended objects, strings.

- A local SUSY theory (since SUSY has spin and Poincare generators) contains gravity. "SUSY is what Einstein would have written if he knew about fermions as well as bosons". The lightest SUSY partners are stable against decays to SM particles.

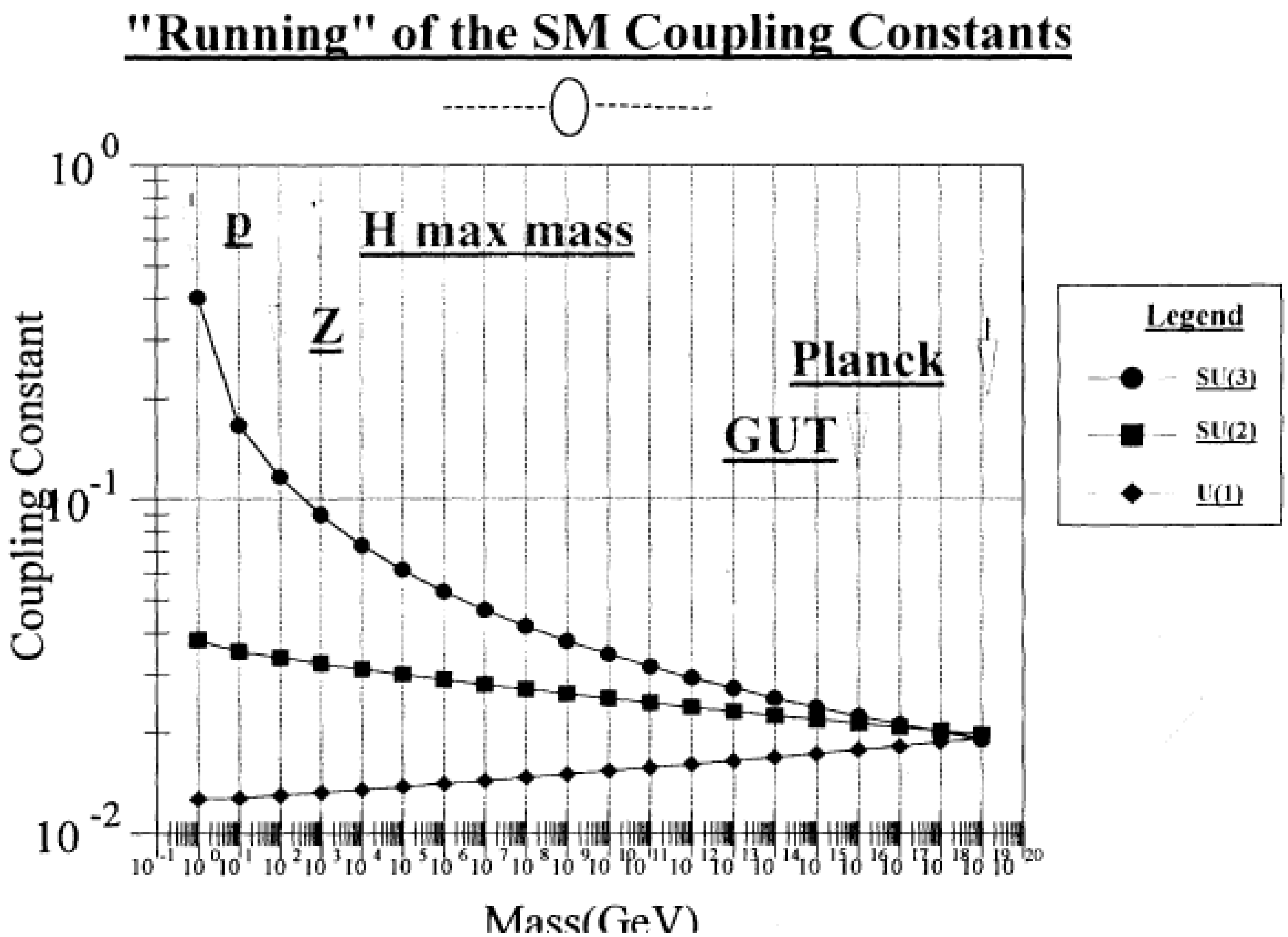
- We do not understand what 90 % of the Universe is made of. The rotation curves of galaxies and clusters of galaxies cannot be caused by the observed stellar masses -"dark matter" - is this the SUSY partners, or the ν mass?

- What is the dynamics that explains the generational spectrum? Where is Bohr when we need him? The Yukawa coupling to e and the top mass, $M_f \sim g_f \langle\phi\rangle$, ranges from 2 x 10^{-6} to 0.7, or about 11 orders of magnitude in the coupling constants, $g_f^2/4\pi$.

Grand Unified Theories

Perhaps the strong and electroweak forces are related. In that case leptons and quarks would make transitions and p would be unstable. The unification mass scale of a GUT must be large enough so that the decay rate for p is < the rate limit set by experiment.

The coupling constants "run" in quantum field theories due to vacuum fluctuations. For example, in EM the e charge is shielded by fluctuations into e^+e^- pairs on a distance scale set by the e, $\lambda_e \sim 1/m_e$. Thus α increases as M decreases, $\alpha(0) = 1/137$, $\alpha(M_Z) = 1/128$.. The GUT scale is ~ 10^{16} GeV, below the mass scale where gravity becomes strong, $U(r) = G_N M^2/r$, $M_{PL}^2 = 1/G_N$, $M_{PL} = 1.2 \times 10^{19}$ GeV.



Possible Scenarios at the LHC

- **There is a single Standard Model (SM) Higgs fundamental scalar field. - boring.**

- **There is another layer uncovered in the "cosmic onion". Quarks and leptons are composites of some new point like entity. This is in analogy to Rutherford scattering - more wide angle, high Pt events then expected in the SM.**

- **There is a deep connection between the Lorentz generators and the spin generators. Each known SM particle has a "super partner" with J' = J + 1/2. The Higgs singlet is also extended in "SUSY" = super symmetry. A new SUSY spectroscopy exists.**

- **The weak interactions violate perturbative unitarity and become strong. Resonances appear in WW, WZ scattering (as in $\pi + \pi$ scattering --> ρ resonance). A new force manifests itself, leading to a new spectroscopy.**

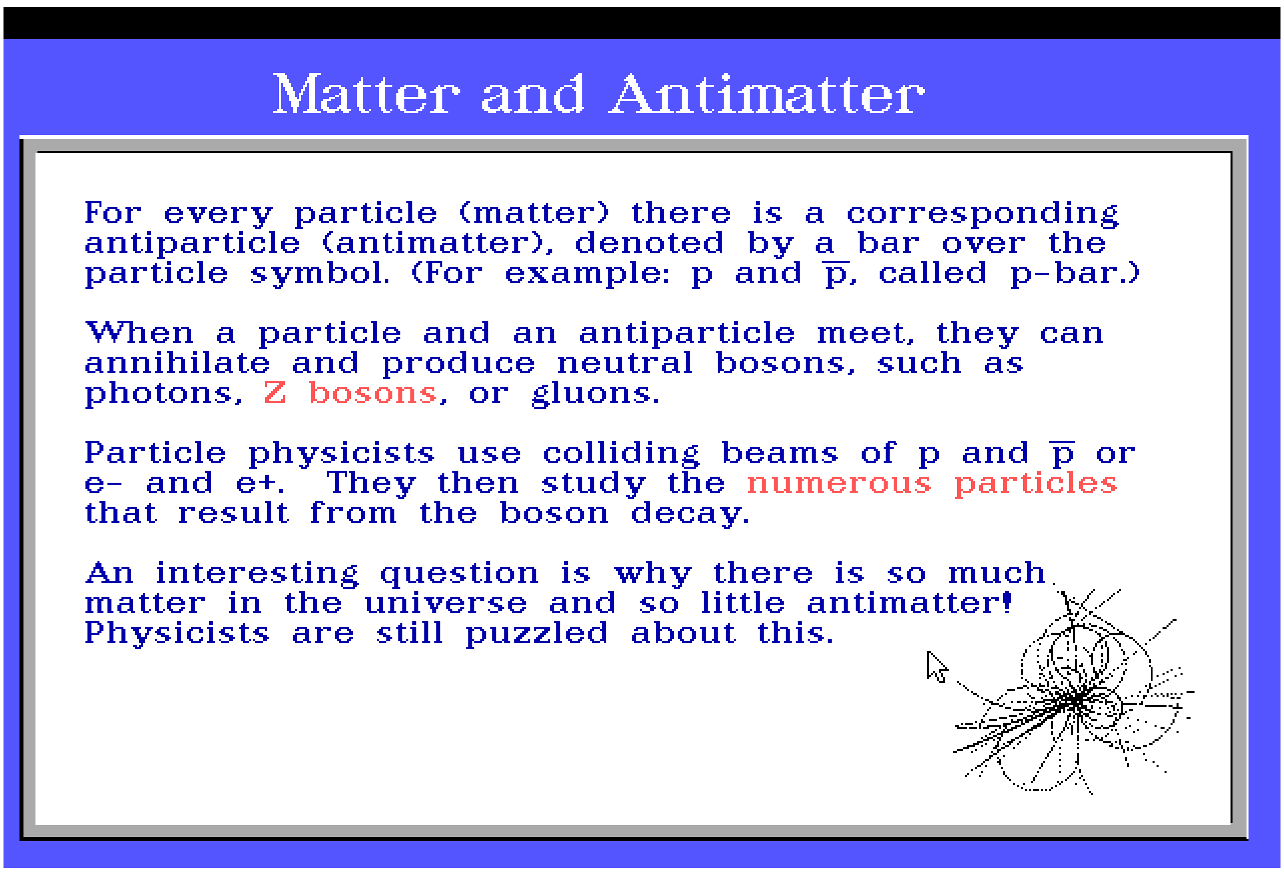
- **Something no one has thought of occurs! interesting.**

Antimatter is required in relativistic quantum mechanics

The Dirac equation has solutions with $E < m$ and $E > m$. They correspond to particles (e.g. electrons e^- and positrons e^+)

The ratio of baryons (p) to photons in the Universe is ~ 10^{-10}. The Universe is mostly light; let there be light.

It is known that one of the necessary ingredients for the lack of antimatter in the Universe is for CP violating interactions to exist.



Quarks are permanently confined baryons are unconfined qqq states

The proton (uud) and neutron (udd) are the lowest energy stable states of baryons. The n decays weakly, p --> n e^- ν.

Baryons are integral charge, half integral spin strongly interacting quark composites.

Baryon Chart

BARYONS = qqq*		quarks	electric charge	mass (GeV/c^2)	spin
p	proton	u u d	+ 1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\,\bar{u}\,\bar{d}$	- 1	0.938	1/2
n	neutron	u d d	0	0.940	1/2
Λ°	lambda	u d s	0	1.116	1/2
Ω^-	omega	s s s	- 1	1.672	3/2
Σ_c	sigma-c	u u c	+ 2	2.455	1/2
Many others !!					

Mesons as Quark Antiquark Composites

The colored quarks are confined. In order to be directly observable, any composite object must be colorless. The possibilities are 3 x 3 x 3 = 1 + 8 + 8 + 10 (SU(3)) - baryons and 3 x 3 = 1 + 8 - mesons. The spins of mesons are 1/2 + 1/2 = 0 , 1 - pseudo scalar or vector "octets".

The pattern of masses and spins can be understood given the underlying masses of the quarks and their spin (1/2).

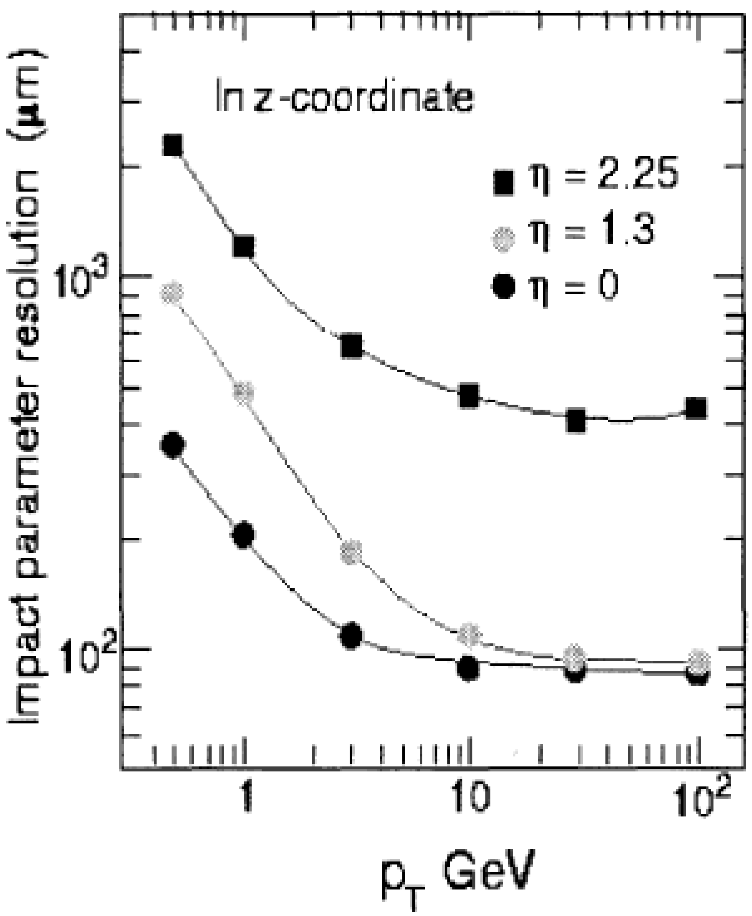
Meson Chart

MESON $= q\bar{q}$		quarks	electric charge	mass (GeV/c^2)	spin
π^+	pion	$u\bar{d}$	+ 1	0.140	0
K^-	kaon	$s\bar{u}$	− 1	0.494	0
K^0	kaon	$d\bar{s}$	0	0.498	0
ρ^+	rho	$u\bar{d}$	0	0.770	1
D^+	D	$c\bar{d}$	+ 1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Silicon pixels and strips will be used to tag the decays of b --> c. The impact parameter (b) **resolution is small with respect to the b lifetime cτ**

[$\sigma(b) \sim$ CONSTANT FOR
$|\eta| < 2.25 \Rightarrow$
GOOD TAGGING ε
FOR $H \to b\bar{b}$]

$\sigma(z)$



$\Rightarrow$ OPTIMIZE LAYOUT TO REDUCE $\sigma(z)$

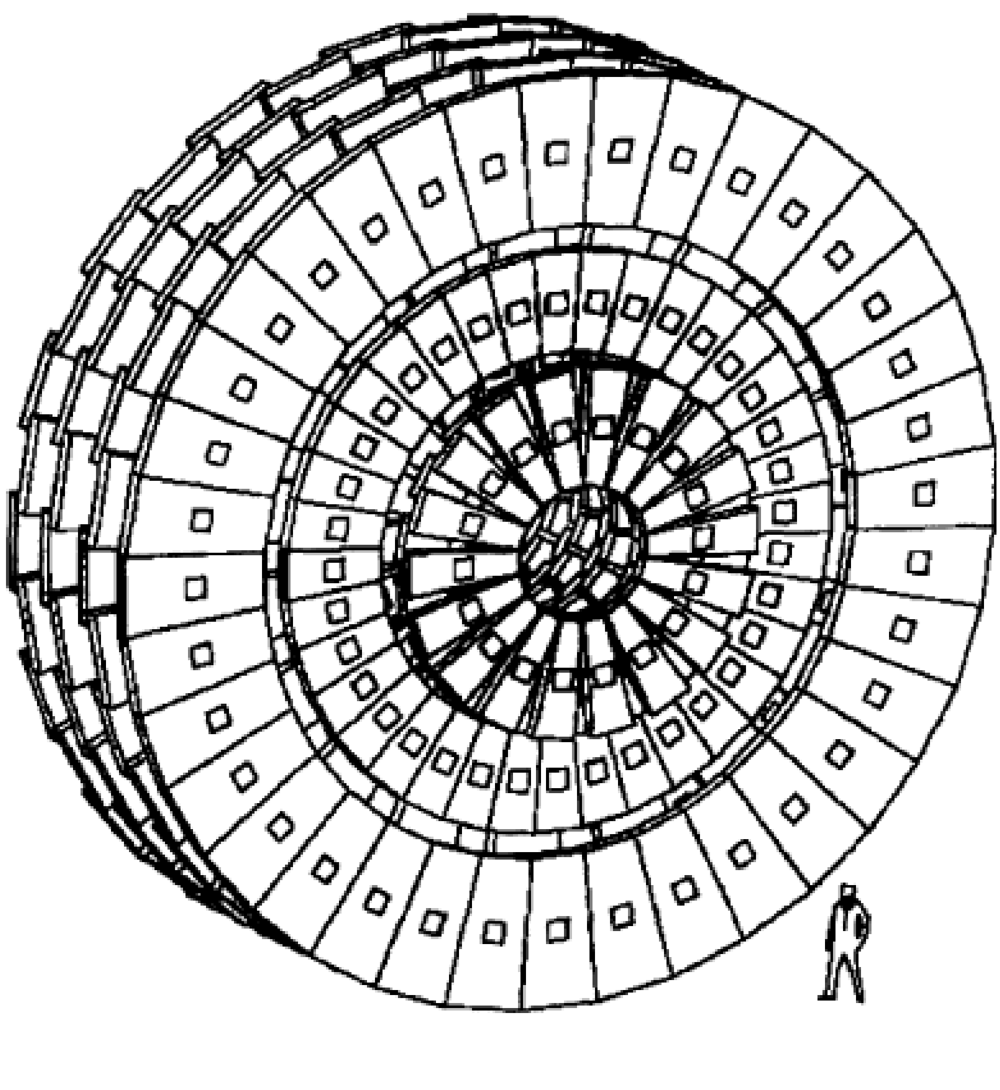
Physics Requirements

Though CMS emphasizes e, μ, γ detection and measurement, detection of jets and missing E_T is essential for:

• $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$	for heavy Higgs discovery
• $H \rightarrow WW \rightarrow \ell\nu jj$	
• $H \rightarrow ZZ \rightarrow \ell\ell jj$	
• $WW \rightarrow H$	with forward jet tags
• $t \rightarrow Wb \rightarrow 3j$	top mass measurement
• $t \rightarrow H^{\pm} \rightarrow \tau\nu$	charged Higgs search
• squarks, gluinos	search through E_T^{miss} signatures
• $H,A \rightarrow \tau^+\tau^-$	MSSM Higgs
• compositeness	search through $pp \rightarrow$ jets
• $W', Z' \rightarrow jj$	

US CMS is Responsible for the Entire

Forward Muon System - CSC + Yoke



4 STATIONS OF MF

6 LAYERS/STATION

OVERLAPS IN ϕ

CMS SUBSYSTEMS

- Magnet: **4T field, coil, vacuum tank, barrel (B) and forward (F) return yoke.** Common Projects.

- Tracking: **pixel Si - B + F, 55 + 22 million channels strip Si - B + F, 2.8 million channels Microstrip Gas Chambers (MSGC) B + F, 11 million channels.**

- ECAL: **crystals of PbWO4 - B + F , 100,000 crystals. Avalanche Photo Diode (APD) transducer. preamp (VFE) + ADC (FE).**

- HCAL: **scintillator + WaveLength Shifting (WLS) fiber - B + F . Optical cable --> Hybrid PhotoDetector (HPD) + preamp --> ADC + trigger pickoff.**

- MUON: **Drift tubes with field shaping and mean timers - B. Cathode Strip Chamber (CSC). Strip centroids and anode wire for coordinates and trigger - F. Both F + B aligned to tracker.**

- Tridas: **L1 pipelined. Use ECAL + HCAL + MUON to trigger on e, J, missing Et, and μ. L2 is "virtual" using event segments. Features high bandwidth event builder switch. L3 is "full" event reconstruction before logging to "permanent media".**